



# THE UNIVERSITY *of* EDINBURGH

This thesis has been submitted in fulfilment of the requirements for a postgraduate degree (e.g. PhD, MPhil, DClinPsychol) at the University of Edinburgh. Please note the following terms and conditions of use:

This work is protected by copyright and other intellectual property rights, which are retained by the thesis author, unless otherwise stated.

A copy can be downloaded for personal non-commercial research or study, without prior permission or charge.

This thesis cannot be reproduced or quoted extensively from without first obtaining permission in writing from the author.

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the author.

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given.

# **STRATEGIC RISK MANAGEMENT FOR TIDAL CURRENT AND WAVE POWER PROJECTS**

**Ralf Bucher**



*Doctor of Philosophy*

**The University of Edinburgh**

2018



## ABSTRACT

Tidal current and wave power, as emerging forms of renewable generation, represent innovations that are confronted by significant technological and financial challenges. Currently, the marine energy sector finds itself in a decisive transition phase having developed full-scale technology demonstrators but still lacking proof of the concept in a commercial project environment. After the decades-long development process with larger than expected setbacks and delays, investors are discouraged because of high capital requirements and the uncertainty of future revenues. Although ideas for improving the investment climate can be found, there is a lack of well-founded arguments and coordinated strategies to work towards a breakthrough in the marine energy market.

The objective of this research is to provide stakeholder-specific prioritised strategy options for de-risking the commercialisation of tidal current and wave power technologies. A key principle applied is to integrate a wide knowledge spectrum comprising the technology, policy and financing sectors and to compile the information in a holistic and transparent manner. To gain a broad understanding of the characteristics of presently ongoing marine energy activities and the correlated strategic planning, a comprehensive survey was conducted. Based on this multi-disciplinary attempt, an all-encompassing appraisal was possible by avoiding over-concentration on stakeholder-specific views or interests. System dynamics modelling was employed to develop a series of cause-effect relationship diagrams of the key interactions and correlations in the field.

It was revealed that the circular relationship between two major risks for array-scale projects – reliability and funding – requires coordinated action to overcome. As funding is necessary for improving system reliability (and vice-versa), showcasing “array-scale success” was identified as the game-changing milestone towards commercial generation. Furthermore, it was found that a number of comparably competent manufacturing firms is required to implement major marine energy projects. This would result from fostering a multi-company market breakthrough concept, based on intensified knowledge sharing and trustful collaborative interaction between competitors.



Additionally, effective separation of complexity into “detail” and “dynamically complex” constituents was found to be fundamental for identifying long-term, effective solutions. It is decisive to accept this primary classification, as measures appropriately applied on one type of complexity can be counterproductive if applied on the other. Most of the available planning tools and analytical methods do not address the management of dynamic complexity, necessary in innovative environments where flexibility and tolerance of vagueness are indispensable. Successful application of several strategies to deal with both types of complexity in comparable innovation-driven environments was considered suitable for de-risking the commercialisation of marine energy.

The challenges for strategy-finding in a demandingly complex and increasingly dynamic environment are addressed in this research by exploiting a case-specific expert knowledge database. The structured information compression and subsequent strategy-finding process is realised based on calculated rankings of impact factors by systems dynamics software and substantiated by representative interview statements. The analysis makes use of multi-level expert knowledge and the application of a control-loop-based methods. The systems approach as applied in this research comprises the combination of interview-based (bottom-up learning) processes and the application of prioritised strategy options in the form of concerted management action (top-down planning).

The approach of processing multi-level interview data by system dynamics modelling represents a powerful method to detect and assess ongoing developments and thus to advance strategy-finding. The systematic and unbiased approach to identify the top-level drivers for commercialising marine energy supports the long-term creation of investor confidence, based on a concept of transparency and credibility.

## **DECLARATION OF AUTHORSHIP**

I, Ralf BUCHER, declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Signed:



Date: May 23, 2018

## ACKNOWLEDGEMENTS

This distance learning postgraduate research was undertaken part-time between 12/2009 and 11/2016 without achieving any external funding. While reflecting a decade of turbine commissioning and consulting experience in large hydro and transmission grids, the academic research area was identified by the author in accordance with the university.

I am grateful for the guidance and support by my supervisors, originally the late Prof Ian Bryden and Dr Scott Couch and since December 2013 Prof Gareth Harrison and Henry Jeffrey.

Great thanks to my love Eliana for her valuable time and Pablo's inspiring interjections: "Immer Stau. Immer warten" to be compensated by "Apfelkuchen, mehr." and "Stäbchen – einfach!". If topics become more complicated, Pablo can state "Das glaub' ich nicht!" followed by the ultimate question about the "WARUM".

Thanks for all support to Mum, Dad and Birgit.

# **TABLE OF CONTENTS**

<b>ABSTRACT</b>	<b>I</b>
<b>DECLARATION OF AUTHORSHIP</b>	<b>III</b>
<b>ACKNOWLEDGEMENTS</b>	<b>IV</b>
<b>TABLE OF CONTENTS</b>	<b>V</b>
<b>INDEX OF FIGURES</b>	<b>VII</b>
<b>INDEX OF TABLES</b>	<b>IX</b>
<b>GLOSSARY</b>	<b>X</b>
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Research questions	3
1.3 Sequence of elaboration	3
1.4 Contribution to knowledge	10
1.5 Publications	11
<b>2 LITERATURE REVIEW</b>	<b>13</b>
2.1 The marine energy commercialisation process	14
2.2 Demonstration projects and pilot installations	22
2.3 Large-scale deployment	26
2.4 Applying the systems approach	29
2.5 Inter-organisational learning and strategic partnerships	41
2.6 Complicacy and complexity	43
2.7 Chapter summary	45
<b>3 METHOD AND MATERIALS</b>	<b>46</b>
3.1 Research design	46
3.2 Analogy to closed-loop control concept	47
3.3 Preparation of survey and data acquisition	49
3.4 Data analytics and selection of software tool	62
3.5 System dynamics modelling	63
3.6 Chapter summary	66
<b>4 PRIMARY INTERVIEW RESULTS &amp; STATISTICAL FINDINGS</b>	<b>68</b>
4.1 Calibrating the research: Target project characteristics	68
4.2 Knowledge transfer and learning from neighbouring sectors	68
4.3 Achievements and planning	71
4.4 Cost aspects	73

4.5	Risks	77
4.6	Chapter summary	83
<b>5</b>	<b>IDENTIFICATION OF PIVOTAL MILESTONES</b>	<b>84</b>
5.1	Necessity for SD-model 1	84
5.2	Full-commercial power generation by marine energy	85
5.3	Calculated allotment of primary interview statements	98
5.4	Sensitivity analysis and robustness of test results	100
5.5	Chapter summary	111
<b>6</b>	<b>THE GAME-CHANGING “ARRAY-SCALE SUCCESS”</b>	<b>112</b>
6.1	Necessity for SD-model 2	112
6.2	Showcase commercial-scale projects / successful demonstrators	113
6.3	Calculated allotment of primary interview statements	118
6.4	Chapter summary	122
<b>7</b>	<b>NEGATIVE IMPACT ON THE DEVELOPMENT</b>	<b>124</b>
7.1	Necessity for SD-model 3	124
7.2	Negative impact on development of marine energy	124
7.3	Calculated allotment of primary interview statements	129
7.4	Chapter summary	132
<b>8</b>	<b>PRIORITISED STRATEGY OPTIONS</b>	<b>133</b>
8.1	Stakeholder-specific measures to close the gap in literature	133
8.2	Technology-driving stakeholders	137
8.3	Policy framework	140
8.4	Financing sector	142
8.5	Business development and strategy planning	143
8.6	Chapter summary	146
<b>9</b>	<b>FROM COLLABORATION TO COMPETITION</b>	<b>147</b>
9.1	Signs of an immature technology	148
9.2	Technology developers: Effective collaboration	149
9.3	Project developers: Competitive concept selection	155
9.4	Chapter summary	160
<b>10</b>	<b>DYNAMICALLY COMPLEX OR “JUST” COMPLICATED?</b>	<b>161</b>
10.1	Background	161
10.2	Reduction of detail complexity	161
10.3	Managing dynamic complexity	162
10.4	Root cause compliant strategy measures	164
10.5	Chapter summary	166

<b>11</b>	<b>DISCUSSION AND LIMITATIONS</b>	<b>167</b>
11.1	Major findings by addressing the research questions	167
11.2	Relation of the findings to similar studies	176
11.3	Unexpected findings	177
11.4	Interpretation of the results	178
11.5	Synthesis of scientific significance and sectorial implications	181
11.6	Limitations of the methodology	185
<b>12</b>	<b>CONCLUSION AND RECOMMENDATIONS</b>	<b>187</b>
12.1	Conclusion	187
12.2	Recommendations	191
12.3	Final thoughts	192
<b>13</b>	<b>REFERENCES</b>	<b>193</b>

## **APPENDICES**

### **A PROJECT PLAN**

### **B BACKGROUND DOCUMENT AND QUESTIONNAIRE**

B.1 Background document

B.2 Questionnaire

### **C EXPERT INTERVIEWS**

C.1 List of participants

C.2 Respondents per question

### **D PRIMARY INTERVIEW RESULTS AND STATISTICAL FINDINGS**

### **E SYSTEM DYNAMICS COMPUTER MODELS**

E.1 Model 1: Full-commercial power generation by marine energy

E.2 Model 2: Showcase commercial-scale projects / successful demonstrators

E.3 Model 3: Negative impact on the development of marine energy

### **F PUBLICATIONS**

F.1 Scientific journal articles

F.2 Peer review conference poster

F.3 Peer review conference papers

## INDEX OF FIGURES

Fig. 1	Sequence diagram of thesis elaboration	4
Fig. 2	Interlinking of bottom-up and top-down processes	34
Fig. 3	Closed-loop diagrams: Standard terms (top) & adaptations (bottom)	48
Fig. 4	Exemplary cause and effect relationships (excerpt from SD-model 1)	89
Fig. 5	SD-model 1: Full-commercial power generation by marine energy	93
Fig. 6	SD-model 1: Insight matrix (detailed analysis in Appendix E.1.3)	94
Fig. 7	SD-model 2: Showcase commercial-scale projects / (...) demonstrators	116
Fig. 8	SD-model 2: Insight matrix	117
Fig. 9	SD-model 3: Negative impact on the development of marine energy	127
Fig. 10	SD-model 3: Insight matrix	128
Fig. 11	True-to-scale impact on marine energy development	135
Fig. 12	Conventional power project phasing	159
Fig. 13	Optimised power project phasing	159

## INDEX OF TABLES

Table 1	FIDIC-compliant and optimised power project phasing	23
Table 2	Analogies of terms in control theory and the research context	48
Table 3	List of interview participants	53
Table 4	Input data for standard sample size calculation	55
Table 5	Input data for qualitative research sample size calculation	57
Table 6	Analysis of stakeholder-specific ratio contacted to feedback	59
Table 7	Overview on successively elaborated system dynamics models	65
Table 8	Statistical ranking of risks	82
Table 9	SD-model 1: Group terms, negative and positive generic terms	88
Table 10	Characteristics of uniform cause and effect relationships	91
Table 11	Characteristics of non-uniform cause and effect relationships	92
Table 12	SD-model 1: Ranking of impact factors	95
Table 13	SD-model 1: Grouping of impact factors	97
Table 14	Comparison of interview replies ranking and modelling results	101
Table 15	Removal of population: Reduction of replies to generic term #36	104
Table 16	Removal of population: Reduction of replies to generic term #24	106
Table 17	Stepwise modification of time impact behaviour	110
Table 18	SD-model 2: Group terms, sub-group terms and generic terms	115
Table 19	SD-model 2: Ranking of top-level driving factors	117
Table 20	SD-model 3: Group terms, sub-group terms and generic terms	125
Table 21	SD-model 3: Ranking of top-level driving factors	128
Table 22	SD-models 2 and 3: Combined ranking of top-level driving factors	134
Table 23	Foundations for sector-specific prioritised strategy options	136
Table 24	Dynamic complexity: Typical attributes and the marine energy case	163



## GLOSSARY

CapEx	Capital expenditures
DB	Design-build (contract)
DBB	Design-bid-build (contract)
DP	Dynamic positioning
EIA	Environmental impact assessment
EPC	Engineering, procurement and construction
FIT	Feed-in tariff
GW / GWh	Gigawatt / gigawatt-hour
H&S	Health and safety
HSSE	Health, safety, security, environment
ICB	International competitive bidding
kW / kWh	Kilowatt / kilowatt-hour
LCOE	Levelised cost of electricity
metocean	Meteorologic-oceanographic
MW / MWh	Megawatt / megawatt-hour
O&M	Operation and maintenance
OEM	Original equipment manufacturer
OpEx	Operation expenditures
RDI&D	Research, development, innovation and demonstration
ROC	Renewables obligation certificate
SI Ocean	Strategic initiative for ocean energy
SD	System dynamics
TEC	Tidal energy converter
TRL	Technology readiness level
TW / TWh	Terawatt / terawatt-hour
VC	Venture capital
WEC	Wave energy converter

# **1 INTRODUCTION**

Following the provision of background information, the research questions that guide and centre the thesis are formulated. In order to allow the reader to follow the thought and work process, the interlinking between the chapters and sections is described. After a brief overview on the achieved contribution to knowledge, this first chapter closes with the list of publications generated in the course of the research.

## **1.1 Background**

In 2013, a major trend reversal could be observed: the International Energy Agency reported that global energy-related emissions stayed flat, whereas the world's economy grew by 3% (IEA, 2008; IEA, 2015). In the same year, in the EU emissions dropped by more than 6% and the economy grew by around 1.3%. Underlining the relevance of the topic, the seven leading industrial nations agreed to cut greenhouse gases by phasing out the use of fossil fuels by the end of the century. The G7 leaders agreed to back the recommendations of the IPCC, the United Nations' climate change panel, to reduce global greenhouse gas emissions at a range of 40 to 70% by 2050, using 2010 as baseline (G7 Summit, 2015). Electricity generation by renewable sources plays a key role in achieving these goals. In 2013, power generated from renewables contributed 25.4% of the EU-28's gross electricity consumption with an average annual increase of 6.3% since 2003 (Eurostat, 2016).

Since 2003, the EU has allocated up to €140m towards marine energy development (European Commission, 2015) and significant industry investment has triggered substantial progress. Even though significant public support programmes are in place and private sector investment of several hundred million euros has been made in the last decade, the progress towards achieving the market breakthrough was not as expected. The commercialisation of marine energy remains a major techno-organisational as well as financial challenge. The industry goal to deliver projects of up to 50 MW by 2020 (European Ocean Energy Association, 2013) requires critical evaluation when considering the delays and setbacks experienced in recent years. Currently, full-scale technology demonstrators are in operation, but the sector lacks proof of the concept in a competitive project investment environment. The required transition from R&D and prototype deployment to commercial implementation

represents a key challenge. If the first arrays do not deliver good results and acceptable financial returns, the focus of investor interest might shift to other forms of renewable generation with lower risk profiles. The significant public and industry investment made might not be compensated. Although recommendations for improving the investment climate can be found, there is a lack of well-founded arguments and realistic strategies to work towards achieving commercial viability. To re-establish investor confidence, a comprehensively balanced but coherent approach to strengthen marine energy is urgently required.

Although marine renewables arise in an era of massive global interest in low-carbon electricity generation, it needs to be considered that the sector is confronted with a highly competitive market in which other renewables (mostly solar photovoltaic) are competitive with non-renewable sources (Lai and McCulloch, 2017). Taking into consideration the political pressure in reducing greenhouse gas emissions and the global potential of marine energy, a decision was made to direct the research towards identifying feasible strategies to streamline the commercialisation and to successfully achieve the market breakthrough. In order to become recognised as a mature generation alternative, the stakeholders need to jointly prove a range of referenceable application cases in competitive project environments. To pass the present pre-profit phase and to head towards regular utility-scale project implementations, coordinated interaction within and between the stakeholders is required.

Managing the market entry process represents an ambitious undertaking for which the unbiased identification of strategic options and their transposition into stakeholder-specific action plans is necessary. To ensure transparency and traceability in identifying the top-level drivers for commercialising the concept, a structured approach considering multi-level expert interview data is required. As such, the credibility of the recommendations will be enhanced.

The maturation and commercialisation process of marine energy can be regarded as a complex dynamic system that has to adapt to an equally dynamic and challenging environment, which underlines the need for continuous change. Collaborative problem-solving approaches are necessary to deal with time-driven and intertwined impact factors.

## **1.2 Research questions**

The literature reviewed suggested that there was a lack of well-founded and comprehensively coordinated strategies to reliably prepare for a marine energy market breakthrough. The aim of the research, i.e. the overall purpose, is to identify and analyse major risk complexes hindering the commercialisation of marine energy and to create strategic knowledge on how to resolve them.

The research questions that guide and centre the thesis are formulated as follows:

- 1. What are the pivotal milestones and prioritised strategy options for commercialising marine energy?*
- 2. What are the determinants for success of large-scale deployment?*
- 3. Does a systems approach, in combination with the use of multi-level interview data, provide new insight for advancing strategy-finding in marine energy?*

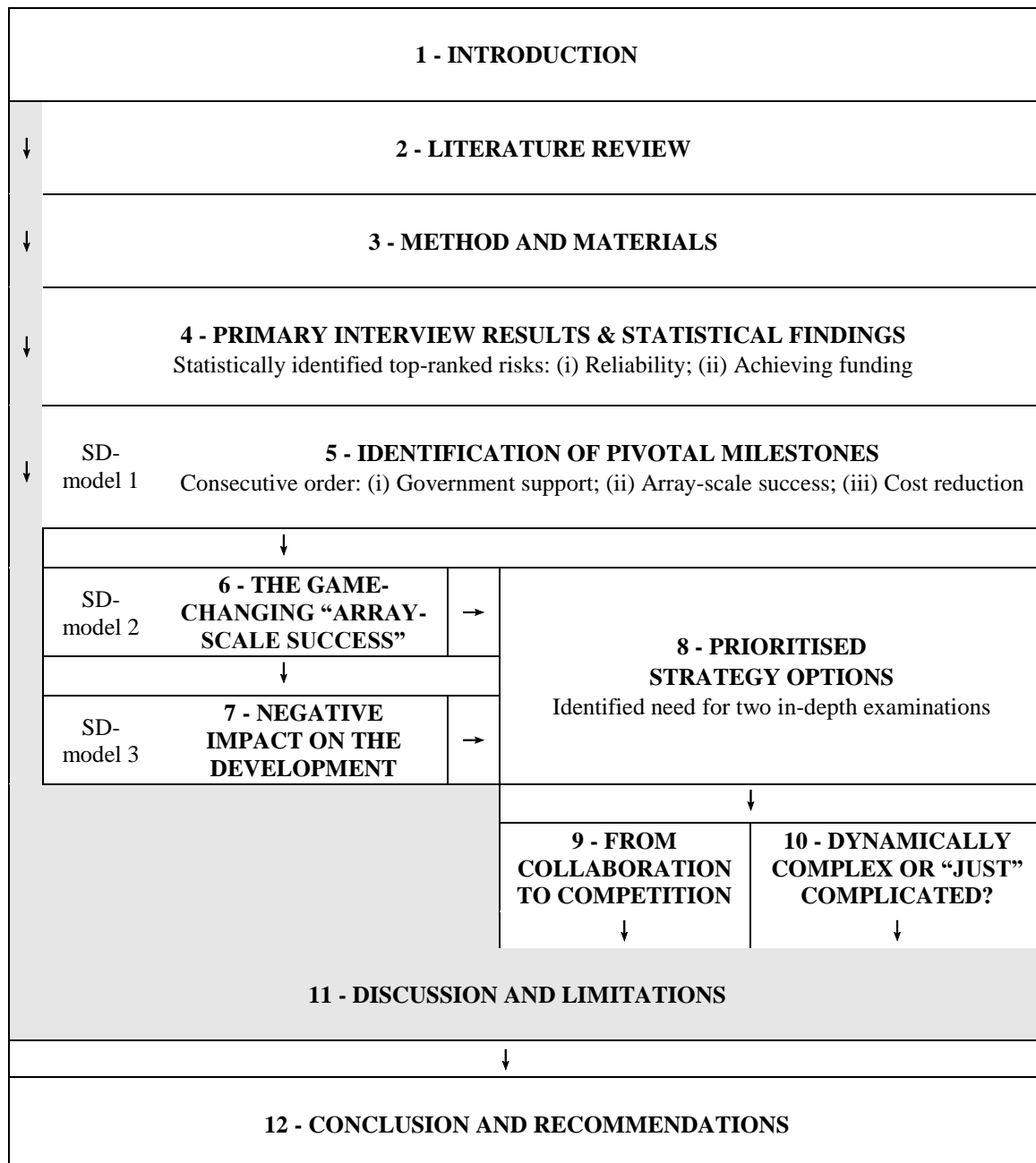
To orientate the marine energy development trajectory in an unbiased and transparent manner, it is necessary to determine top-level drivers substantiated by expert interview statements. On that basis, prioritised strategy options can be elaborated and transposed into stakeholder-specific action plans. At the time of initiating this research, no comparable initiatives were in place to provide high-level orientation for commercialising the technology and to achieve market acceptance.

## **1.3 Sequence of elaboration**

The intention of this section is to provide the logical context and thematic coherence between the individual thesis chapters in order to allow the reader to follow the thought and work process.

Concentrating on the main thesis topic, a PhD project plan (Appendix A) was developed at the outset of the research. This plan was principally followed throughout the development of the thesis.

The actual sequence of elaboration is displayed in Fig. 1.



**Fig. 1. Sequence diagram of thesis elaboration**

Key aspects of the individual chapters, relevant for understanding the further direction of the research, are described as follows.

### Chapter 1 – Introduction

With a focus on the main working phases as laid down in the project plan, subject-specific background knowledge is presented and the problem in commercialising marine energy is specified. This leads to the definition of the research questions.

Subsequently, the sequence of elaboration and the scientific contribution to knowledge are outlined in compressed manner. The list of publications closes the chapter.

## Chapter 2 – Literature review

The literature review, as an integral part to the work, is written to explain the context of the problem examined and to justify the reason for the research. It is arranged to isolate and highlight essential issues and findings. The literature review establishes the theoretical framework and methodological concept of the work and summarises what has been done by others. Although there is a lot of published work on the status quo and the general prospects of marine energy, it was identified that there was a lack of contributions providing strategies to de-risk and commercialise the sector. No concise methodology existed for conducting an unbiased and transparent strategy-finding process in a comparably innovative and capital-intensive energy technology sector.

An overview is given on concepts to de-risk demonstration projects by advancing high-risk phases to early project stages and the determinants for success in large-scale deployment are described. The applied systems approach is presented by describing the concepts of feedback-based strategy-finding and bottom-up learning or top-down planning. Examples for inter-organisational learning and strategic partnerships are given and the relevance of adequately handling complicity and complexity is outlined.

## Chapter 3 – Method and materials

The finalisation of the technology development and the outstanding market integration of marine energy comprise the management of multi-level techno-organisational challenges under financial constraints. The correlated processes need to be embedded in existing “innovation network contexts” (e.g. the ongoing market penetration of renewable energies; the megatrend of decarbonising generation; and the policy of implementing the energy transition) and can thus be considered as constituting complex dynamic systems. Prevailing systemic problems need to be addressed in a coherent manner by high-level coordination between stakeholders. The present research is designed to adequately operate in such environments.

The method allows analysis of the entire spectrum of volatile risk complexes and neutral identification of strategic targets and pivotal milestones. The chosen approach

comprises a combination of transparently processing cross-category expert interview data and the sequenced determination of prioritised strategy options. The findings are based on the calculated rankings of impact factors, correlated representative interview statements and scholarly literature. The method and materials applied in this research enable a circular interplay between knowledge compression and targeted knowledge diffusion. The strategy-finding process is flexible and re-adjustable to new developments and altering priorities.

The definition of the concept of how to analyse the interview data took place before the PhD elaboration phase and is noted in the basic project plan. After identifying and comparing a number of eligible possibilities, the decision to make use of the system dynamics (SD) approach was taken. The main benefits of system dynamics is that it enhances causal thinking, looks behind individual events and brings hidden correlations to the surface as it focuses on dynamic causalities.

As the choice of SD-modelling came before the elaboration of the questionnaire, its content was directed towards the known capabilities and characteristics of this method. The questionnaire was prepared with the intention of gaining a reliable status description of where the sector finds itself, what the main problems are and what perspectives exist on further development. All replies were sorted within a 2- or where necessary 3-stage hierarchical ordering process. In the course of the sorting process, fractured data were put back together which was a source for the emergence of new ideas directing the further research. Conditioned as such, the structured data was used for the configuration of cause-effect relationship diagrams, also referred to as causal diagrams.

In the course of a statistical assessment, it was examined if the number of conducted interviews is sufficient to substantiate the findings.

#### Chapter 4 – Primary interview results & statistical findings

The questionnaire was elaborated to gain first-hand and experience-based knowledge. In the course of contacting potential interview participants, effort was put into getting feedback from all stakeholder groups active on different levels in the development and commercialisation of marine energy. It comprises a similar number of quantitative and qualitative questions.

To be in the position to draw direct conclusions, at the first stage original stand-alone interview replies were put into context and compressed without software support. Efficiently identifying the marine energy market breakthrough required determination of the pivotal milestones and the understanding of their characteristics. The subsequent findings from the system dynamics-backed analyses were cross-checked with the unfiltered primary results.

#### Chapter 5 – Identification of pivotal milestones

This chapter begins the fundamental part of the thesis, in which three systems dynamics models are developed. The data input for the first SD-model is provided by the replies received to question number five as in Appendix B.2. Following the indication in the questionnaire, the interviewees were asked to name the main impact factors on reaching the global target of “full-commercial marine energy” by thinking about qualitative influencing factors (e.g. global policy framework, environment directives and energy security). 18 impact factors, essential for achieving commercial generation, were identified and concentrated into the three pivotal milestone terms “government support”, “array-scale success” and “cost reduction”. A sensitivity analysis and robustness test of the results closes the chapter.

#### Chapter 6 – The game-changing “array-scale success”

In the interest of an in-depth investigation around the characteristics of the “array-scale success”, this term itself is applied as new target factor for the second SD-model. The qualitative outcome of the investigation around “array-scale success” is that by this game-changing event, the identified circular relationship between “reliability” and “funding” (statistically identified as top-ranked individual risks in the course of the expert interviews) will be resolved. Both risk complexes are directly interlinked and will be simultaneously mitigated, as funding is required for improving device reliability and vice-versa. Finally, achieving the “array-scale success” is a prerequisite for marine energy market breakthrough. Based on the quantitative results of the systems dynamics calculation, representative interview statements as per the top-level driver ranking are listed and put into context.



## Chapter 7 – Negative impact on the development

In order to make full use of the interview data record and to further substantiate the results of the SD-model 2, a diametrically opposite target perspective is taken for this third SD-model. In this examination, exclusively factors with negative impact on the development of marine energy are considered. As for the previous SD-model, representative interview statements are correlated according to the results of the system dynamics calculation.

## Chapter 8 – Prioritised strategy options

The determination of the prioritised strategy options is based on the averaged impact level rankings by the system dynamics software for SD-models 2 and 3. “Technology learning” was identified by these calculations as the highest-ranked top-level driver for achieving “array-scale success” and as having the highest potential for creating negative impact on the development of marine energy, if not appropriately managed. The second ranked top-level driver is “marine operation experience”, also with a strong positive and negative impact potential.

The proposed strategy options are presented in stakeholder-specific order after consideration of the findings in chapter 6 and 7 as well as scholarly literature and the author’s own research. They are formulated to support the commercialisation process and to mitigate decisive risk complexes hindering the market breakthrough.

## Chapter 9 – From collaboration to competition

The focus of this in depth-examination is on providing arguments to strengthen the collaboration and alignment between industry, utilities and academia. Pre-competitive collaboration as an established concept is applied in various industrial sectors. The reason for investigating concepts for collaboration is initiated by the calculated result ranking of the top-level driving factors “technology learning” and “marine operations experience”. In the respective underlying interview statements, the “limited knowledge sharing in industry” was criticised and the need to intensify “cooperation between developers” as well as to share “lessons learned between projects” was emphasised. Considering the status quo of marine energy under the aspect of technology development processes, even without the system dynamics computing

results, the conclusion to investigate upon competitive collaboration could be reached. A higher level of cooperation between project and technology developers minimises the risk for replication and duplication in manufacturing. It is expected that the sharing of engineering knowledge and environmental data supports continuous design improvements and fosters the technology convergence process. The risk of repeating mistakes is minimised.

#### Chapter 10 – Dynamically complex or “just” complicated?

The justification for investigating this aspect in depth is given by the multi-layered nature of the challenge to commercialise marine energy. To achieve this ambition, broad and profound knowledge about the correlated tasks and processes is required. Starting with the basic separation between complicity and dynamic complexity, the second in-depth examination analyses the actual marine energy problem and risk complexes. Based on the scientific literature and experience in comparable industrial sectors, recommendations for appropriate strategies are made.

#### Chapter 11 – Discussion and limitations

The function of the discussion chapter is to outline the impact and scientific significance of the findings and obtained results. Oriented along the primary research questions, the contribution to knowledge and the implication of the findings are detailed in terms of how the identified gap in literature has been filled. The achieved results are interpreted in view of the understanding of the problem before and after the research. Furthermore, it is examined how the answers fit in existing knowledge on the topic elaborated by others in parallel to this work. The discussion links the aim of the research assimilated in the three research questions with the literature review, the applied methodology and the elaborated results. The main function is to answer the research questions based on the achieved results and to explain the significance of the new findings. Finally, the limitations of the methodology are outlined.

#### Chapter 12 – Conclusion and recommendations

The final chapter represents a synthesis of the key points emerging from the investigation. Recommendations for further research and on how to overcome the limitations of the methodology are given.

## 1.4 Contribution to knowledge

The key original contribution from the thesis is methodological. It comprises the use of a systematic and transparent methodology for capturing, analysing and interpreting information obtained from expert stakeholders via a structured survey.

In order to make best use of the available momentum in the sector, the identification of *pivotal milestones and prioritised strategy options* is required. Driven by the outcome of the literature review, a conclusive set of measures to fundamentally support the maturation and commercialisation of the marine energy sector is presented. The underlying expert interview information is allocated according to the calculated ranking of combined top-level driving factors. The synthesis of data is suitable to be transposed into individual businesses. As key elements of the foundation for sustainable growth of marine energy are laid in the present pre-commercial stage, the *determinants for success of large-scale deployment* are presented throughout the development path for the different stages starting with the market entry to the phase of expanding the market position up to finally safeguarding the long-term market participation. A prerequisite for generating *new insight by the systems approach to advance strategy-finding* is to ensure a high level of transparency and traceability as the basis for the trustworthiness of the results. As in conventional management, mainly aspects of detail complexity are considered, focus is put on providing concepts to understand and manage dynamic complexity. As the presented analytical process is standardised, regular updates and adaptations are feasible without high effort.

While several attempts to elaborate high-level recommendations for *de-risking the market entry of marine energy* are documented in literature, the present study is the first to comprehensively address the problems by holistically identifying stakeholder-specific strategy options. The research reminds the stakeholders that the market entry of marine energy is a one-off chance because other forms of renewable energy generation develop in parallel and some have achieved the break-even threshold. Relevant *arguments for cooperation to pass the singular hurdle* of achieving the market breakthrough focus on joint benefits by the subsequent implementation of commercial-scale projects. The *application of measures in line with the nature of complexity* is essential as inappropriate measures can cause counterproductive results.

## 1.5 Publications

5 scientific journal articles, 1 peer-review conference poster and 6 peer-review conference papers resulted from this thesis. The contributions shown in bold are available in Appendix F.

### 1.5.1 Scientific journal articles

- **Bucher, R., Jeffrey, H., Bryden, I.G., Harrison, G.P. (2016) Creation of investor confidence: The top-level drivers for reaching maturity in marine energy, Renewable Energy 88, pp120–129, <http://dx.doi.org/10.1016/j.renene.2015.11.033>**
- **Bucher, R., Bryden, I.G. (2016) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, International Journal of Marine Energy, International Journal of Marine Energy, Vol. 13, pp180–192, <http://dx.doi.org/10.1016/j.ijome.2015.05.002>**
- **Bucher, R., Bryden, I.G. (2015) Governing the market entry of marine energy by symptom-adapted interventions: (i) Reduction of detail complexity; and (ii) Managing dynamically complex tasks, Journal of Energy Challenges and Mechanics, Vol. 2(2) article 4, pp56–61, ISSN 2056-9386**
- **Bucher, R., Bryden, I.G. (2014a) Strategic orientation for the ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge, Journal of Energy Challenges and Mechanics, Vol. 1(2) article 8, pp103–112, ISSN 2056-9386**
- **Bucher, R., Couch, S.J. (2013)<sup>1</sup> Adjusting the financial risk of tidal current projects by optimising the “installed capacity/capacity factor” - ratio already during the feasibility stage, International Journal of Marine Energy, Vol. 2, pp24–42, ISSN 2214-1669, <http://dx.doi.org/10.1016/j.ijome.2013.05.008>**

---

<sup>1</sup> The journal paper was published before the start of the main thesis work stream to get access to the scientific community. The examination is based on the author's master thesis (Bucher, 2008; Bucher, 2009a; Bucher, 2009b; Bucher, 2014), but the new findings on de-risking the marine sector and creating investor confidence were elaborated during the PhD phase. For the referenced project, originally promoted by Voith Siemens Hydro (2007) and the Federal Ministry for Economic Affairs and Energy of Germany (2007) with a rating of 600 MW, only park concepts with less than 50 MW would comply with such a requirement. The practical relevance of the identified benchmark value was proven years after the conduction the study by the report of Ernst & Young (2013) in which it states that a tidal-stream power project with a generating capacity of 53 MW is expected to be developed in Wando. In Culley et al. (2016) the automated design of tidal arrays, taking into account the turbine number, is further developed.

### **1.5.2 Peer-review conference poster**

- **Bucher, R. (2012)<sup>2</sup> De-risking marine energy investments by extending the regular project implementation by a competitive technology qualification routine, 4<sup>th</sup> International Conference on Ocean Energy (ICOE), Ireland**

### **1.5.3 Peer-review conference papers**

- **Bucher, R., Jeffrey, H. (2015) The strategic objective of competitive collaboration: Managing the solid market launch of marine energy, 11<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC), Nantes, France**
- **Bucher, R., Jeffrey, H. (2014) Creation of investor confidence: The top-level drivers for reaching maturity, 5<sup>th</sup> International Conference on Ocean Energy (ICOE), Halifax, Canada**
- **Bucher, R., Bryden, I.G. (2014b) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, 2<sup>nd</sup> Asian Wave and Tidal Energy Conference (AWTEC), Tokyo, Japan**
- **Bucher, R. (2013) Strategic risk management in ocean energy: A system dynamics approach to the evaluation of 40+ expert interviews, 10<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC), Aalborg, Denmark**
- **Bucher, R. (2012) De-risking marine energy investments by extending the regular project implementation by a competitive technology qualification routine, 4<sup>th</sup> International Conference on Ocean Energy (ICOE), Ireland**
- **Bucher, R., Couch S.J. (2011) Adjusting the financial risk of tidal current projects by optimising the “installed capacity / capacity factor” - ratio, 9<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC), Southampton, UK**

---

<sup>2</sup> The conference poster was published before the start of the main thesis work stream to get access to the scientific community in order to contact potential interview partners. The examination focuses on how to optimise the project phasing of array-scale projects by introducing a “competitive technology qualification routine”. The standard implementation phasing is first critically analysed and then optimised by taking into account the specific requirements of technology innovation and maturation processes.

## 2 LITERATURE REVIEW

As at inception of the work in 2010/2011 it was observed that there was a deficit in the body of theoretical and empirical literature on the strategy for commercialising marine energy, the research topic was defined accordingly. The in-depth literature review is driven by the formulated research questions. It provides background information and summarises work that has been undertaken by others in the subject area.

Despite the significant progress achieved in the maturation and commercialisation of marine energy, many important problems and questions are unanswered. In the course of this review, no reference was found in which concrete and stakeholder-specific strategy options were elaborated based on the transparent analysis of cross-category expert data. It remains open, to (i) find effective measures to resolve the circular relationship between proving device reliability and achieving funding; to (ii) identify stakeholder-wide balanced strategies to de-risk large-scale deployment; and (iii) to sharpen the target orientation towards healthy and productive competition based on effective knowledge sharing, just to name a few. The sum of deficits in the scholarly literature provides the reason for the research. To overcome the pre-profit phase and to enable the market roll-out, targeted action within, between and by the stakeholder groups is required.

Oriented along the research questions, the following material is critically reviewed:

- Scholarly literature on the status quo of marine energy and on strategies aiming to orientate the development and commercialisation trajectory.
- Scientific articles and pilot project reviews on array-type deployment.
- Reference case studies in which the systems approach was successfully applied.

The present contribution aims to close the identified gaps in literature by using interview-based expert knowledge and the systems approach to gain new insight and provide scientific evidence.

If adequately addressed, the elaborated results can support commercialisation of marine energy based on stakeholder-specific strategy recommendations.

## 2.1 The marine energy commercialisation process

In this section, the focus is put on central development milestones and the strategic orientation for efficiently commercialising marine energy.

The socio-economic relevance and industrial job creation potential of marine energy is significant. While estimates of the global resource may vary, the total market size is given at 90 to 120 GW of tidal current turbine generating capacity (Lewis et al., 2015; Magagna and Uihlein, 2015). A proportion of 25 GW has been quantified in more detail, which would correlate to an installation of about 15,000 turbines. Regarding wave power, the global extractable capacity is estimated at 100 GW (Gunn, 2012).

The involvement of major industrials (like ABB, Alstom, Andritz, DCNS, Lockheed Martin, Siemens<sup>3</sup> and Voith<sup>4</sup>) as well as the successful testing of full-scale prototypes underline the serious commitment and indicate significant engineering competence. In a press release on the marine energy development path, it was outlined that a 300 kW tidal current prototype turbine has delivered over 1.5 GWh to the grid and has shown during prolonged test runs<sup>5</sup> an availability rate of 98%. During the two-years operation, a full maintenance and validation cycle has proven the fitness for purpose of the design (IEA-OES, 2013). A reference value for turbines in onshore wind farms is an annual turbine availability of 97% and in offshore wind about 90% (Tavner, Xiang and Spinato, 2007; UK Energy Research Centre, 2012). Because of the similarity of horizontal axis tidal current turbines and medium size wind turbines, it is reasonable to use experience in the wind industry to assess reliability values in the tidal sector (Karikari-Boateng et al., 2013). Leete, Xu and Wheeler (2013) emphasise that recorded reliability data are paramount because confidence in the capability of the marine energy technology is fundamental for achieving market acceptance. The regular publishing of in-situ monitored device reliability data is essential.

---

<sup>3</sup> In February 2012, Siemens acquired a majority share in the tidal device manufacturer Marine Current Turbines (MCT). Since November 2014, Siemens was looking to exit the marine energy sector, saying the development of the market and the supply chain has taken longer to grow than expected. In April 2015, Atlantis Resources Limited announced that it has reached agreement to acquire the entire issued share capital of MCT from Siemens.

<sup>4</sup> In March 2013, Voith Hydro decided to shut down its wave power business (Wavegen), choosing to concentrate on tidal power. A representative outlined that Voith will re-intensify its wave power activities as soon as the market situation is appropriate. In the 2015 Group Management Report it is stated that the tidal power product division will be continued on a significantly smaller scale only.

<sup>5</sup> No information was found about the actual duration of the prolonged test runs (within the two years operation period), which makes a direct %-value availability rate comparison with on-/offshore wind data impossible.

Leete, Xu and Wheeler (2013) performed a series of interviews with senior finance and industry actors in the marine renewables sector and examined investor attitudes towards wave and tidal. They reported that none of the investors previously engaged in venture capital funding of early-stage marine energy device development in the UK were likely to do so again. Venture capitalists were discouraged from investing because of high capital requirements and the uncertainty of costs and respective future revenues. Some stated that a track record of continuous device operation of at least 6 months is a pre-requisite for further engagements. The authors conclude that at the current stage of development strategic investment in partnership with industry investors is essential for heading towards commercialisation. Magagna and Uihlein (2015) summarise that high costs associated with marine energy, combined with the unproven status of the technology, limit investor confidence. Investors profiled by Masini and Menichetti (2012) showed a clear preference for more mature, proven technologies with only 3 of 93 investors analysed having any exposure to wave and tidal energy. According to Sjöö (2008), the following factors are usually assessed before venture capital investment in renewable energy technologies: regulatory framework, competitive situation, technological risks, market uncertainty and supply chain constraints. Santos et al. (2014) emphasise that energy investments as such have specific characteristics because of their (i) irreversibility; (ii) high level of uncertainty; and (iii) flexible timing, as an investor might be able to postpone his decision in order to obtain better information. Johnstone et al. (2010) also outline that, in the context of renewable energy policy and technology innovation, investors are likely to postpone risky investments in the presence of uncertain signals from government. The correlation of funding sources for the different technology development and maturation stages are described by Wüstenhagen and Menichetti (2012) as: grants (for R&D), venture capital (for part-scale prototypes), private equity (for full-scale prototypes), debt finance (for first pioneering arrays) and institutional finance (for utility-scale projects).

Aside from the described investor attitude, private company investment in marine energy technologies of more than €700m in the decade has triggered significant progress (SI Ocean, 2014). Given the relatively small scale of today's marine energy projects, investors are able to achieve similar or greater returns with larger



developments in which technologies that are more proven are applied. The slow technological progress combined with difficulties in attracting financing for array demonstration projects is seen as limiting investor confidence in the sector.

Reducing cost is a critical success factor for achieving market competitiveness. According to the Department of Energy & Climate Change (2011), the projected levelised cost of electricity (LCOE<sup>6</sup>) for UK marine energy in the year 2020 will range between 20 and 42 c€/kWh. Spain expects LCOE for 2020 of 21 to 33 c€/kWh (IEA-OES, 2013). Previsic et al. (2012) have similarly suggested a commercial opening cost of electricity for wave power in the order of 20 to 30 c€/kWh. RenewableUK (2013) believe that the current LCOE for leading tidal current devices is around 36 c€/kWh (and in the range of 25 to 47 c€/kWh according to IRENA, 2014), compared with 48 c€/kWh for wave power converters. As onshore wind energy represents the reference for cost-competitive renewable power, it is notable that the global average LCOE dropped from 19 c€/kWh in 1992 to 6 c€/kWh in 2014 (Global Wind Report, 2014). Offshore wind farms at very good locations currently achieve LCOE of 11 to 19 c€/kWh (Fraunhofer, 2013; IRENA, 2012). LCOE for onshore wind in the UK are projected to be 9 to 15 c€/kWh by 2020 and for offshore wind of 13 to 22 c€/kWh (Department of Energy & Climate Change, 2011). Taking into consideration the projected LCOE in the UK for 2020, the cost for tidal current might touch the upper end of the offshore wind range. Presently, the kWh-costs in marine energy are far too high to compete with other renewable or even non-renewable generation options (Previsic and Shoele, 2013).

For the forthcoming years, governmental support programs will be indispensable to further drive research and development (IEA-OES, 2014b). In offshore wind – with a global installed capacity of 5.4 GW (IEA, 2013) – it is expected that a further 15 years of subsidies will be required (Karikari-Boateng et al., 2013). The UK Government has recognised wave and tidal as emerging technologies and awarded 5 ROCs/MWh<sup>7</sup> for

---

<sup>6</sup> LCOE is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.

<sup>7</sup> Renewables Obligation Certificate: A ROC is the green certificate issued for eligible renewable electricity generated within the UK and supplied to customers in the UK by a licensed supplier. The default is that one ROC is issued for each MWh of eligible renewable output. For instance, offshore wind installations receive 2 ROCs/MWh, onshore wind installations 0.9 ROCs/MWh and sewage gas-fired plants half a ROC per MWh.

the first 30 MW of capacity by any tidal current or wave power project (RenewableUK, 2013). Additional capacity will receive 2 ROCs. The average ROC price in 2015 was around £42/MWh<sup>8</sup> which led to a feed-in tariff of approximately 28 c€/kWh for wave and tidal. In the course of the interviews undertaken in this research, one expert stated that for achieving market success in Nova Scotia, tidal devices must not cost more than \$5 million CAD/MW (~3.5 m€/MW) with resulting energy costs of less than \$140/MWh (~10 c€/kWh). It is notable that this target seems to be set unrealistically low.

MacGillivray et al. (2014) highlight the sensitivity of marine energy development to the achievable capital cost of the first devices and the rate of cost reduction with deployment. They emphasise that continued and sustained growth of the sector mainly depends on reaching early cost competitiveness with other forms of renewable energy and on demonstrating the long-term technological viability.

Apart from purely assessing LCOE values, it needs to be evaluated to what extent grid-integrated renewable power systems affect the operational characteristics of existing electricity supply networks. Power generation by tidal currents is – contrary to wind and photovoltaic – predictable in the long-term, which gives it a premium value. Predictability is a huge advantage by supporting efficient network management (Bayod-Rújula, 2009; Hammons, 2008). Bucher (2015) describes the overarching flexibility options enabling the integrating of large-scale renewable generation, e.g. in the form of wide area energy balancing by a pan-European overlay grid or by fast-ramping energy storage assets. The findings are of relevance for marine energy.

Regarding the global perspective for marine energy, it is indicative to look at the world's largest energy user, China. As the country is reshaping its energy sector, a commitment has been made to halt the growth in greenhouse-gas emissions by 2030 (Nature, 2016). Considering a coastline of 14,500 km length and the fact that it leads the world in the deployment of renewable energy<sup>9</sup>, marine energy might profit.

In a renewable energy context, Negro, Alkemade and Hekkert (2012) criticise the tendency for entrepreneurs to compete with each other in the very early stages instead

---

<sup>8</sup> <http://www.epowerauctions.co.uk> [28.01.2016]

<sup>9</sup> In 2015, China invested some US\$110 billion in renewable energy projects.

of forming coalitions and alliances. This hinders them becoming more influential regarding changing regulations, to obtain more resources and to create a niche market. According to the underlying survey, cooperative strategies are adopted only after having encountered difficulties, disappointments or a lack of support from government. Within the respective literature, a number of different explanatory models describing the disadvantages of such early-stage competition were found. Hekkert (2007) and Negro (2007) described in the context of technological innovation systems<sup>10</sup>, that most actors seem to be unaware of the fact that tough competition in very early phases of development reduces the chances of survival for most emergent technologies. For the example of biomass digestion and gasification, they explain that emerging technologies usually go through a 10- to 30-year trajectory of development, diffusion and implementation, which requires long-term policy goals. Collaboration between stakeholders, focussing on knowledge development and knowledge diffusion, is seen as a central “system function”. Similar conclusions are drawn by Amanatidou and Guy (2008) who emphasise the increasing importance of knowledge-based industries and the benefits of research that aligns existing perceptions by maximising collaboration and minimising competition. Potential levels for cooperation in product development between competitors are described in Bourreau and Doğan (2010). They put forward the trade-off between the benefits obtained through development cost sharing and additional spending by intensified competition because of the simultaneously reduced product differentiation.

Concentrating on the target defined by the first research question in identifying pivotal milestones and prioritised strategy options for commercialising marine energy, the contribution by Vantoch-Wood and Connor (2013) is of relevance. In the course of investigating the UK public policy for wave energy by analysing networks of activity, they identified a lack of public-sector coordination and transparency as key factors diminishing investor and stakeholder legitimacy. Consequently, the strategy-finding approach developed in this research is based on the unbiased integration of stakeholder-wide knowledge in order to mitigate the shortcomings quoted.

---

<sup>10</sup> Technological innovation systems consist of networks of firms, R&D infrastructure, educational institutions and policy-making bodies that interact in a specific technology area to generate, diffuse and utilise technology.

The most comparable approach of elaborating high-level recommendations for commercialising the emerging wave and tidal energy sectors was made by an EU-funded market deployment strategy (SI Ocean, 2014). The ambition was to unite the sector behind a common agenda and to provide industry-led strategies that provide tangible recommendations to facilitate the development and large-scale deployment of wave and tidal energy technologies. In order to facilitate deployment, SI Ocean<sup>11</sup> recommends creating a network of European test and demonstration facilities, to collaborate for installation, operation and maintenance, to foster cross-industry cooperation for serial manufacturing at EU level and to implement cross-sector platforms for marine energy grid integration.

Evident in the SI Ocean activities and the conclusions drawn from their interviews and workshops, it is indispensable to identify top-level trajectories to commercialise wave and tidal energy. It is necessary to put the maturation process and the preparation of the market breakthrough on a solid basis with a number of equally strong manufacturing firms, competing in offering similarly rated and comparably reliable devices. This research investigates on how to best direct the sectorial development trajectories in order to become competitive in the price-sensitive electricity market. The recommendations given to address technology development concentrated on initiating new RDI&D (research, development, innovation and demonstration) programmes, validating the reliability of devices, creating standards and guidelines for performance evaluation and fostering industrial cooperation and knowledge exchange. The goal is to enable maximal wave and tidal installed capacity by 2020, paving the way for exponential market growth in the 2030 and 2050 timeframes.

The cited literature confirms the value in the chosen research approach to determine milestones and strategy options based on multi-level expert interviews. It can be summarised that the reviewed literature lacks the provision of well-founded, stakeholder-wide integrated and carefully balanced strategies to efficiently overcome the pre-commercial phase. Even though the contributions confirm that endurance and a long-term perspective are required to enable fundamental work towards achieving

---

<sup>11</sup> Strategic Initiative for Ocean Energy: The project is coordinated by Ocean Energy Europe in close cooperation with 6 partners: The European Commission's Join Research Centre, the UK Carbon Trust, Portugal's Wave Energy Centre, University of Edinburgh, Renewable UK and DHI.

competitive generation cost, concrete strategic recommendations for stakeholder orientation are not given. The potential common benefits by sharing knowledge and joining forces are never outlined. Ignoring this opportunity puts investments at high risk. As over-optimistic assumptions on the pace of progress created disappointment and mistrust in the past, in today's investment community, substantiated projections and realistic targets are requested. This gap in the literature constitutes a key argument for conducting the present research in order to precisely determine the key milestones and to provide substantiated arguments to support stakeholder strategy planning.

Jay and Jeffrey (2010) outline that the lack of design consensus is likely to restrict the pace of development and learning. On the other side, Jacobsson and Bergek (2004) emphasise potential longer-term advantages by retaining design variety. In research on technology convergence, Augustine et al. (2010) concluded that a robust approach for systematic improvement is to combine the strengths of all available concepts instead of selecting the best among alternatives. Kaplan and Tripsas (2008) note that the evolution of technology is significantly influenced by institutional actors such as government agencies, standards bodies, industry associations and media. They outline that in case a "collective technological frame" or a supporting "technological innovation system" does not emerge, the convergence on a dominant design might be prevented. The emergence of dominant designs in complex technical environments was examined by Murmann and Frenken (2006) from a systems theory perspective considering technology standardisation. Teece (1986) outlines that once a dominant design has emerged, competition shifts to a completely new set of parameters of which the most important one is price. The author provides noteworthy business strategy examples that show that "imitators" can make higher profit in the long-term than the original firms that first commercialise a new product or technology.

The need to support incremental and radical innovation in parallel, both classified as "sustaining innovation" in contrast to "disruptive innovation" (Interaction Design Foundation, 2014) is emphasised by Jeffrey, Jay and Winskel (2013). Incremental innovation is relevant for closest-to-market full-scale prototypes and radical innovation for technologies with potential for step-change performance improvements. By the controlled consolidation of stand-alone knowledge, technology convergence processes can be accelerated and the identification of hybrid solutions simplified.

In wind power, continuous innovation and a steady increase of the standard turbine rating is regarded as normal. From 1984 until today, the rotor diameter has increased from 15 to 164 m and the nameplate rating from 50 kW to 8 MW (MHI Vestas Offshore, 2015). The next development step in offshore wind is expected to be the introduction of 15 MW turbines (Gamesa, 2014). In the course of a EU-financed research programme (FP6), it was found that the design of very large wind turbines up to 20 MW would require technological step changes but is considered as feasible (European Commission, 2011).

In the tidal current sector, less coherent development prevails. Even as the focus of major industrials is on 1 MW+ demonstrator devices, a number of tidal developers (e.g. Schottel, Nova Innovation and Tocardo) follow a distinctly different approach by working on small-scale technologies (30 to 500 kW) in order to reduce cost and risk associated with manufacturing, testing and deployment (European Commission, 2015). Reference is also made to the reports by SI Ocean (2013a and 2013b) in which a twin-track development strategy is recommended: one for large-scale devices to raise the credibility of the sector and to ensure that EU deployment capacity targets are met and a second for small-scale technologies that allow a rapid expansion and proving of early arrays. The essential strategy recommendations published by the SI Ocean initiative are cited in tabular form in Bucher and Jeffrey (2015).

From a long-term perspective, the marine energy industry sector might grow in significance and capacity in a similar manner to wind power. Bucher and Bryden (2016) chart the development of the number of MW-scale on- and offshore wind and tidal turbine manufacturers, and their global installed capacities from 1970 to 2015, based on data provided by SI Ocean (2013b), IEA-OES (2014a) and the European Commission (2014a). It is encouraging to see that in the field of marine energy the first 1 MW full-scale prototype was deployed in the year 2008 and only seven years later there are at least 6 renowned manufacturing companies providing comparable equipment. In this regard, the momentum for growth in marine energy is significantly higher than it was in the wind sector, where this development required about 16 years. Within a global market environment of only six to seven competing MW-scale turbine manufacturing firms in wind power, a significant annual capacity increase of about 400 MW was for example realised in the year 1986 (Moghaddama, 2012).

## **2.2 Demonstration projects and pilot installations**

### **2.2.1 Integrating complexity management into near-commercial projects**

Jay and Jeffrey (2010) describe that in the marine energy sector there are a number of technologies and components, which offer opportunities for shared learning. At the same time, they emphasise that support and transfer of generic knowledge is limited by commercial competition. In line with these findings on limited sharing of knowledge, in the present survey, a general lack of collaboration was confirmed by the interviewees. The artificial competition with on-/offshore wind was criticised as negatively influencing uninterrupted progress in marine energy. A modern organisational error management culture (e.g. sharing of error knowledge, effective error handling, error prevention) as defined by Van Dyck et al. (2005) can help to reduce the promotion of error consequences and minimise the reported constraint that “too many people are doing the same things”. Išoraitė (2009) outlines that where industrial competitors accept the high significance of jointly achieving a sustainable market success, the motivation for entering into strategic alliances will rise.

### **2.2.2 Conventional and optimised power project phasing**

Conventional power projects are based on applying mature technology within an established framework of routine implementation activities. The equipment procurement is typically realised via ICB<sup>12</sup> and according to a balanced system of international standards and guidelines. A standard project phasing according to the guidelines of the Fédération Internationale des Ingénieurs-Conseils (FIDIC, 2010) is shown in Fig. 12 and Bucher (2012). The expected failure risk levels are displayed in three categories: low risk (green), medium risk (yellow) and high risk (red). High-risk phases are located towards the end of the project implementation, which is unfavourable for innovative projects because valuable feedback gained during the project execution cannot be taken into account at the time to mitigate technological, organisational and financial risks.

The principal idea behind the optimised power project phasing is to extend the regular project execution by a competition-oriented concept in the course of which different

---

<sup>12</sup> International Competitive Bidding: ICB enables effective competition and gives equal opportunities for businesses to participate and win in government procurement activities.

manufacturers' power conversion devices are deployed and operated in real-sea conditions directly in the project area for a defined period of time (3 to 6 months). The individual device performance is independently assessed by a certification company. The manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated according to previously agreed rates. In Fig. 13 and Bucher (2012) the optimised project phasing sequence is displayed. Contrary to conventional power projects, project phase VI is modified and phase VII is further sub-divided as per the terms in Table 1.

**Table 1: FIDIC-compliant and optimised power project phasing**

Phase	FIDIC-compliant (conventional)	Optimised power project phasing (competitive technology qualification routine)
I	Pre-design	
II	Concept design	
III	Schematic design	
IV	Detailed design	
V	Building permit	
VI	Procurement / Award of contract	Procurement / Award of partial contract
VII	Construction & installation	A - Construction & installation (stage I)
		B - Competitive technology qualification routine
		C - Award of principal contract
		D - Construction & installation (stage II)
VIII	Commissioning, trial operation, commercial operation	

In order to guarantee an effective multi-manufacturer technology qualification routine, it must be ensured that the basic array infrastructure, providing manufacturer-independent interfaces (e.g. common systems such as transformer stations, inner-park cabling, grid interface, station control, protective relaying and telecommunication to dispatcher) is operational in advance. By this sequenced and modular concept, device manufacturers can maintain their company-specific component and system design philosophies and only have to adapt to the specified common systems and interfaces.

Phases I to V comprise the development of the modular design concept and the elaboration of the detailed tender documents for the specimen marine energy converters to participate in the competitive selection process. A key task is to guarantee that scheme-wide uniform interfaces are specified so that each device can be considered as an independent module. In the general part of the tender documents, the



details of the competitive technology qualification routine are presented. Furthermore, the marine climate and the characteristics of the deployment area are described.

In Phase VI the contracts for the basic infrastructure (i.e. cable systems, transformer stations, grid connection, control centre) and the TECs or WECs participating in the qualification routine are signed.

Phase VII-A covers the installation and commissioning of the common infrastructure and subsequently of the TECs or WECs participating in the competition. Phase VII-B represents the actual competitive technology qualification routine. In phase VII-C, according to pre-defined criteria, the performance and quality of all deployed device types are analysed in a transparent manner. The best-rated competitor(s) is/are directly awarded for Phase VII-D contracts. For tidal current and wave power projects, the evaluation criteria might consider:

- Grade for delivering the project on time, within budget and high quality. Soft factors such as cooperation, troubleshooting capability, extraordinary events.
- Achieved energy yield data, device capacity factors and the number of grid-connected operation hours as well as planned and unplanned shutdowns.
- Equipment condition at the end of trial operation and assessment of the amount of maintenance activities and cost of spare parts used.

The non-successful contest participants are finally compensated to cover their accumulated design, manufacture, installation and maintenance costs. Their devices are dismantled. In phase VII-D the best-rated devices are deployed in large numbers to be operated under commercial conditions. As the final decision on the concept selection will be based on the experience gained from the time of tendering to the end of the trial operation period, the evaluation criteria can cover a widespread contractual and technical spectrum.

### **2.2.3 Advance high-risk phases to early project stages**

The specific characteristics when amending a commercial power project with an innovative competitive technology qualification routine need to be reflected by an appropriate contract structure. In the course of fixing the terms, the investor needs to assess its particular institutional and technical strengths and weaknesses (Huse, 2000).

Many studies have evaluated the advantages and disadvantages of the traditional design-bid-build (DBB) contracting method with design-build (DB). Al-Reshaid (2005) states that DB works best when the investor is knowledgeable, vigilant and participates actively in all project phases from the design through construction and commissioning. Achieving an optimum project result depends on selecting the method most adequate for the individual project.

In the case where a utility-scale marine energy project is complemented with a competitive technology qualification routine, the following concept provides benefits:

- DBB contract for the basic infrastructure, common systems and interfaces

Design-bid-build is the traditional approach to construction contracts in which the investor provides the design and coordination of the project. Usually the investor commissions an engineering consultancy to prepare the tender specification under a design contract. In a public procurement process, a contractor to supply, install and commission the systems and equipment is selected (Khaled, 2005; El-Sawalhi, 2007). DBB provides the investor with extensive control over the design and construction process where he takes responsibility for interface clarifications and the coordination of the different contractors in case of multi-contracts.

As the infrastructure and common systems to which the individual TECs or WECs will be connected mainly comprise standard components known from the offshore wind or other marine sectors, managing innovation is not a key task. By precisely specifying the technological interfaces, a high modularity of the devices to be connected is enabled. As DBB provides the investor with extended control over the design and construction process, valuable knowledge can be accumulated, which is of high importance for the subsequent phases and further projects.

- Identical DB contracts for firms participating in the qualification routine

Design-build contracts, also referenced to as turn-key or EPC (engineering, procurement and construction), place the entire project, including design and construction, in the hands of the contractor. The critical success factor is the preparation of the request for proposal that describes the scope of work (Yng Ling, 2008). As the interface coordination is under the responsibility of the contractor,

investor's involvement is reduced. However, as the project risk is significantly shifted to the contractor, this might increase the project price.

Regarding the variety of marine energy converter concepts, a detailed specification (as under DBB) might be a limiting factor. As the responsibility for delivering fit-for-purpose systems is with the individual firms, innovative management, design, manufacturing, deployment and commissioning concepts are not excluded. Under a DB contract, risks can be managed more effectively and new knowledge arising during contract execution can be incorporated in a flexible manner. Identical contracts for all participating device manufacturers prepare for an effective project supervision and simplifies the performance assessment at the end of Phase VII-B.

With the proposed contract splitting, the investor can satisfy the needs for the implementation of proven technology but allows for innovative solutions in the course of the competitive device selection process by enabling high degrees of freedom at the manufacturer's side. If a project is divided into separate stages, it is beneficial for the investor to mainly focus his involvement on the critical and decisive project stages, which are concentrated in the competitive technology qualification routine.

By the optimised project phasing, stage I construction and installation experience (phase VII-A) as well as operational results gained during the competitive technology qualification routine (phase VII-B) can be considered before awarding the principal contract (phase VII-C) for the stage II construction and installation (phase VII-D). Contrary to the conventional arrangement, the risk levels decline towards the end of the project implementation. Apart from the partial contract scope of supply, which exclusively covers the marine energy converters competing in the qualification routine, the common systems can be tendered in packages as usual in phase VI.

### **2.3 Large-scale deployment**

In this section, the focus is put the determinants for success in large-scale deployment.

Söderlund (2010) highlights that large-scale transformation projects – for which the maturation and market integration of marine energy is a good example – are characterised by involving several hundred individuals, different technologies,

numerous knowledge bases, complex contractual structures and a wide range of development activities with parallel operations. Cross-functional knowledge integration and cross-team communication are considered as highly significant because different organisation or individuals tend to develop their own time orientations and hence rely on out-of-phase cycles of knowledge processing. Sterman (1992) demonstrates, also in the context of large-scale engineering and construction projects, that these are generally characterised by many interdependent components, multiple feedback processes, non-linear relationships, accumulation or delay functions and belong as such to the group of complex dynamic systems. He emphasises that cause and effect can be subtle and obvious interventions can produce non-obvious consequences. In research on knowledge integration processes in large-scale engineering and construction projects, Roussel and Deltour (2012) examined the prerequisites for efficient information exchange between specialist teams and the steering organisation. They outline that the specific and dispersed knowledge of many individuals must be regularly collected, interpreted and assimilated. In research on innovation networks and complex technological innovation, Rycroft (2007) found that the emergence of complex technologies is embedded into equally complex innovation networks. As per his findings, high levels of innovative performance are usually associated with network-based collaboration in the form of strategic alliances involving manufacturers, universities, government agencies and other organisations. Carlsson et al. (2002) identified in the course of innovation studies that market-linked technological systems are not static but evolve continuously to be able to survive.

Within the literature, there is consensus that large-scale transformation or engineering/construction projects are characterised by their complicity and especially dynamic complexity. Bi-directorial communication channels, cross-functional databases and the systematic integration of knowledge are seen as key for achieving success. The literature clearly specifies the need for knowledge integration and network-based collaboration, but convincing arguments on the benefits (and disadvantages) of their implementation are not provided. In particular, the prevailing feedback situation and multi-level correlations require the application of system-based approaches, as performed in this research.

Alkemade, Kleinschmidt and Hekkert (2007) explain from an innovation studies perspective, that new technology often has difficulty in competing with embedded technologies and formulate that most inventions are relatively inefficient at the date when they are first recognised as constituting an innovation. Negro, Alkemade and Hekkert (2012) formulate that renewable energy technologies find it hard to break through in an energy market dominated by fossil fuel technologies that reap the benefits from economies of scale, long periods of technological learning and socio-institutional embedding. If the gap between new and established technology is very large and if there is a “paucity of nursing” or missing “bridging segments” that allow for a gradual generation of increasing returns, a new technology may never have the chance to rectify the initial disadvantages (Andersson and Jacobsson, 2000). Scholars in evolutionary economics have highlighted the importance of “niches” that act as “incubation rooms” for radical novelties, shielding them from mainstream market selection. Such protected environments enable to overcome conventional organisational inertia (e.g. Nelson, 1989; Steinhilber, Wells and Thankappan, 2013). Bergek, Hekkert and Jacobsson (2008) confirm that technology development can best take place within specially created learning spaces that allow a new technology to stabilise a development trajectory directed towards reaching maturity or even to identify a dominant design. Erickson and Maitland (1989) suggest in a heavy industry context that “nursing markets” need to be created to support the technology breakthrough, taking advantage of windows of opportunity that drive the adjustments in the socio-technical regime as formulated by Geels and Kemp (2007).

Although taking into account that significant development has taking place in the so-called incubation rooms in the form of marine energy test facilities or subsidised pilot projects, the underlying time pressure cannot be neglected. As artificially created learning environments can be maintained only for a limited time, it should be in the elementary interest of all project developers and manufacturing firms to make best use of the present period of “trial and error” by an extraordinary level of sharing knowledge and experience with competitors and by establishing effective cooperative interaction (Bucher and Jeffrey, 2014). Consequently, as realised in the present research, there needs to be made a differentiation between pilot and commercial projects in the course of identifying the relevant factors of success.

Within research on project management, Ahern and Leavy (2014) make the important distinction between detail-complex (or complicated) and dynamically complex projects. They criticise that traditional project management privileges planning and downplays the role of learning. Planning and problem-solving must be dealt with differently, as also emphasised by Swinth (1971). This is in line with the finding of Hayek (1945) who stated that dynamically complex tasks cannot be completely specified in advance. Corsatea (2014) formulated that reality-proven proposals and suggestions for the development of the sector are needed to adequately deal with the economic difficulties, technical challenges, supply chain bottlenecks and the complexity of the marine energy sector.

## **2.4 Applying the systems approach**

In this section, the focus is put on the characteristics and reference cases in which a systems approach was used to process multi-level data to enable new insight and to advance strategy-finding.

### **2.4.1 Feedback-based strategy-finding**

To overcome the challenges in commercialising marine energy, the European Commission (2014b) started to define targeted actions at EU level. The intention was to bring together a wide range of stakeholders in a series of workshops (between 2014 and 2016) to foster cooperation and to develop a shared understanding of the problems in order to collectively devise workable solutions. The bottom-up approach facilitated the accumulation of a critical mass of actors and the development of a shared response to the issues at stake, thus “creating a sense of ownership among the involved stakeholders”. In a second phase from 2017 to 2020, the Commission will set out an action plan to guide the further development of the sector. This plan shall help the industrialisation, so that marine energy can provide cost-effective, low-carbon electricity as well as new jobs and economic growth. The corresponding report confirms one elementary foundation of the present research by the statement that “common goals are best served through an inclusive approach”. In this regard, Bonar, Bryden and Borthwick (2015) argue that a greater public acceptance of renewable energy developments can be achieved by open communication, information sharing and improved public engagement practices. They describe that a strategic and

collaborative research effort between developers, academia and the public sector leads to improvements in best practice for device and array design. In a comparable stakeholder-integrative approach, Richards, Noble and Belcher (2012) use bulk data collected by semi-structured interviews with 18 wind energy experts for their multi-dimensional analytic research on technological, economic, social and public barriers to renewable energy development. Furthermore, the dynamics of knowledge integration in cross-functional projects is examined by Huang and Newell (2003) and they point out that it is vital to systematically mobilise different knowledge assets (e.g. by semi-structured interviews or informal dialogues) in order to be able to cope with continuous innovation processes. They explain that the management of so-called social capital requires adaptive learning in order to successfully implement strategy adjustment or change initiatives.

In the course of developing the research method and investigating further options for strategy-finding, relevant management case studies published in scientific papers were analysed. In the context of implementing a complex offshore oilfield construction project, Barlow (2000) suggests that insufficient inter-organisational cooperation causes many performance problems. This author emphasises that it is essential to establish the right tools and techniques for achieving a rapid integration of the knowledge and skills possessed by the participating organisations.

After the described bottom-up information gathering, top-down management processes follow. Yim et al. (2004) emphasise in a strategic management context, that upper level decision-makers are routinely required to make sense of a variety of unstructured, complex and often conflicting information in constrained timeframes. To enable managers to make decisions in dynamic and non-trivial environments, they suggest using system dynamics modelling. As described by Capra (1996), the only way to fully understand why a problem occurs and persists is to understand the interrelationship of the constituting parts and to put it into the context of a larger whole. The research on strategy simulation by Yasarcan (2013) confirms the inadequacy of human intuitive skills in decision-making in the presence of dynamic complexity. Bennett (1998) explains in the same context that decisions often evolve through a complex, non-linear and fragmented process. With regard to conceptualising a target management problem, he emphasises that partial knowledge needs to be re-organised

and combined into an integrated knowledge model. Interviews and discussions are described as adequate elements to define causal relationships in order to prepare for system dynamics modelling. In an investigation on risks as barriers to renewable energy investments, Komendantova et al. (2009) use several stages of structured and unstructured expert interviews. The authors conclude that knowledge-based decision-making enables better outcomes in dynamic and convoluted environments. The fact that strategic decisions usually have no precedent and are often not easily analysed or modelled is highlighted by Dean and Sharfman (1993). They emphasise that the linkage between knowledge management and the achievement of strategic objectives is facilitated through system dynamics.

In line with the theoretical principles used in grounded theory (GT)<sup>13</sup>, the generation of new knowledge starts with the very first word in the very first interview (so-called “open-coding”). Based on a repetitive process of data acquisition, in GT, analytical categories are built successively and put into context in order to be refined in a new theory (Martin and Turner, 1986). As explained by Allan (2003), GT is different from traditional research models, where the researcher chooses an existing theoretical framework and only then collects data to show how the theory does or does not apply to the phenomenon under study. Key elements of the present research method indicate a strong overlap with GT-principles.

In the literature it is uniformly concluded that the transposition of knowledge from a wide spectrum of stakeholders into the decision finding process is key for strategy-finding. The use of system dynamics tools is repeatedly recommended for that purpose.

#### **2.4.2 Bottom-up learning and top-down planning**

Experiments in behavioural science emphasise that the integration of knowledge to a collective level requires access to different knowledge domains (Grant and Baden-Fuller, 2004). As formulated by Okhuysen and Eisenhardt (2002), it is necessary to coordinate the contributing bodies in order to spiral up specialised knowledge. Analyses by Kim, Sting and Loch (2014) in an industrial manufacturing context showed that strategy-formation is an iterative process of integrating bottom-up

---

<sup>13</sup> Grounded theory is a systematic methodology in the social sciences involving the construction of theory through the analysis of data.



learning and top-down planning, because “top management’s strategic intentions are shaped by lessons from daily operations”.

To effectively approach the target of commercial power generation by marine energy, bottom-up and top-down processes need to be applied in a consecutive manner:

- (i) “Bottom-up learning” is a type of information processing based on incoming data from the field to form higher-level perceptions. In a study on the impact of global climate change on water resource systems, adaptation strategies were identified empirically in a bottom-up approach based on semi-structured interviews, group discussions and scholarly literature (Girard et al., 2015).

Similarly, in this study expert interview data are used to form the manifold input for the configuration of the system dynamics models. Based on the calculated ranking of results, top-level drivers and prioritised strategy options are elaborated.

- (ii) “Top-down planning” starts from the general, abstract, superordinate towards the special, concrete, subordinate. The process can be described as the steered coordination of actions to achieve specific goals imposed by a central authority (Kim, Sting and Loch, 2014).

In this work, by drawing on the identified top-level drivers and prioritised strategy options, the management of each stakeholder is put in a position to introduce corresponding measures and action plans. Depending on the success rate, the management body can reinforce or modify its functions as appropriate or even initiate a repetition of the interview-based strategy-finding process.

The bottom-up and top-down processes are complementary and can create a symbiotic continuum when applied in a sequenced strategy. Hereby it has to be taken into account that bottom-up learning is mainly of a qualitative<sup>14</sup> nature and that top-down planning represents a quantitative<sup>15</sup> concept as management bodies usually communicate in the form of precise and measurable stipulations.

---

<sup>14</sup> Qualitative research is primarily used to gain an understanding of underlying reasons, opinions and motivations. It provides insights into the problem and helps to develop ideas or hypotheses.

<sup>15</sup> Quantitative research is used to quantify attitudes and opinions based on measurable data to formulate facts.

Sun and Zhang (2004) explain the characteristics of implicit<sup>16</sup> and explicit<sup>17</sup> learning and the resulting consequences for cognitive skill acquisition. Transferred to the marine energy research context, implicit knowledge, even though difficult to verbalise, can be retained in the course of the interview-based bottom-up learning process. After its software-backed conversion into well communicable explicit knowledge, it can then be applied as per the top-down planning principle.

Regarding the suitability of different methods of reasoning, Burney (2008) refers to induction (from empiricism towards theory, i.e. gaining of broader generalisations and theories from specific observations or individual cases) and deduction (from theory towards empiricism, i.e. starting with a general statement or hypothesis followed by the examination of possibilities to reach a specific conclusion). In the present research, the uplift of empirical knowledge to strategic guidelines (induction) is part of bottom-up learning. On the other side, putting the acquired knowledge into practise means to follow refined (theoretical) strategies, which is in line with the deduction principle.

The system dynamics models developed in this thesis are designed in order to reflect one-to-one the content and structure of the interview data. The causal diagrams are based on qualitative data, which is in line with the requirements of the bottom-up learning principle. The result ranking calculated by the software tool represents superordinate knowledge and correlates to information usually available to management. Based on such quantitative knowledge, “top executives create plans and orders which are passed down the hierarchy”, in line with the top-down principle (Nonaka and Takeuchi, 1995).

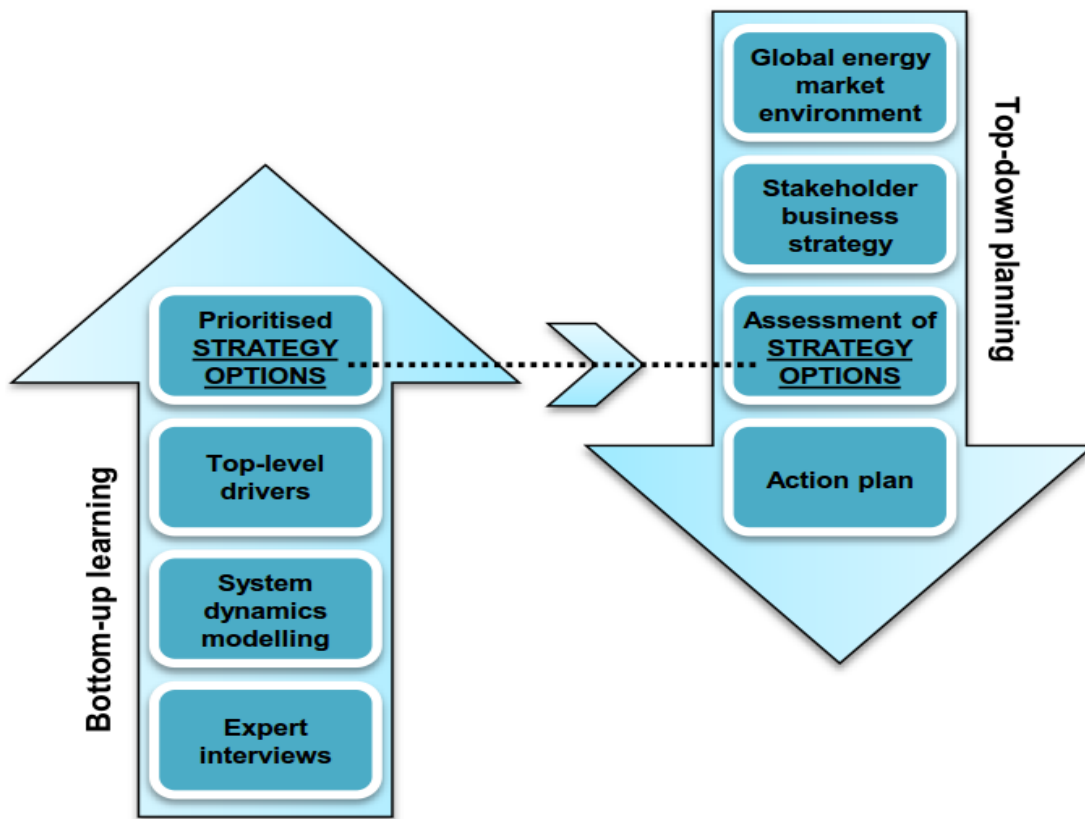
In the context of assessing climate change adaptation options, Bhawe, Mishra and Raghuwanshi (2014) explain that combining bottom-up and top-down approaches provides valuable guidance for policy-making based on much needed legitimacy through stakeholder involvement. In Fig. 2, the corresponding elements and processes used in this work are represented in an adapted manner including a transfer element for the sequenced transposition of the determined prioritised strategy options.

---

<sup>16</sup> Implicit (or tacit) knowledge is difficult to transfer to another person by means of writing it down or verbalising.

<sup>17</sup> Explicit knowledge can be readily articulated, codified, accessed and verbalised.

The methodology applied for marine energy enables a dynamic and circular interplay between knowledge compression by bottom-up learning and targeted knowledge diffusion in the form of top-down planning.



**Fig. 2: Interlinking of bottom-up and top-down processes**

The design of the present research is principally in line with the idea of qualitative feedback modelling as described by Groesser (2011b). Qualitative feedback modelling is realised at a fundamental level by considering the complete marine energy maturation and commercialisation process in an abstract manner as a complex dynamic system. Its core characteristics are approached by comprehensive semi-structured interviews conducted with all relevant stakeholder groups (Bucher and Bryden, 2014a). The elaborated strategy-finding approach is compact and directly targets the final goal of reaching full-commercial power generation.

Explaining the analogy of this process by a closed-loop control circuit (Schwenke and Groesser, 2014; Senge and Sterman, 1992; Diehl and Sterman, 1995; Sterman, 1989) with clearly defined technical terms helps to remove barriers and is described further in the following section.

### **2.4.3 System dynamics modelling**

Rapoport (1986) defines a system as a combination of several elements where each element is affected by at least one other and where each element has an effect on the functioning of the whole. Out of many definitions of complex (dynamic) systems, the following provide the best understanding within the context of the present research: (i) a complex system is literally one in which there are multiple interactions between many different components (Rind, 1999); (ii) a complex system is a system in process that constantly evolves and unfolds over time (Arthur, 1999); and (iii) a complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large or one in which there are multiple pathways by which the system can evolve (Whitesides and Ismagilov, 1999). Crespi, Galstyan and Lerman (2008) formulate that global system behaviour emerges out of the interactions among constituent components (e.g. between stakeholder groups) and between components and the environment (e.g. by regularly adapting the marine energy development trajectory to the continuously changing socio-technical system).

As an initial step in approaching the characteristics of complex dynamic systems (in the mid-1950s), system dynamics was developed as a methodology and mathematical modelling technique for framing, understanding and discussing complex issues and problems. At the beginning of the sixties, the system dynamics approach was described as a tool for knowledge-based decision-making (Forrester, 1961; Forrester, 1971). Richardson and Sterman (1996) define system dynamics as a computer-aided approach to policy analysis and design. Mainzer (1999) outlines that economic and social processes represent highly dimensional systems with many components for which trends cannot be calculated exactly. It is emphasised that qualitative insight is considered as valuable and that knowledge on trends helps to protect from surprises. Furthermore, according to the theory of complex dynamic systems, global trends can be modelled by a limited number of statistical order parameters. Originally developed to help corporate managers to improve their understanding of industrial processes, system dynamics is now applied throughout the public and private sector (Radzicki and Taylor, 2008). Otto (2008) used system dynamics as a decision aid tool to evaluate complex market entry strategies for the pharmaceutical industry. Li et al. (2012)

confirm that after decades of development and improvement, the system dynamics method is now widely used in the study of economy, society, ecology and many other complex systems.

As described by Markard, Stadelmann and Truffer (2009), innovation processes are often highly complex because the technological development interacts with social, economic and political dynamics. The authors emphasise that technological innovation systems and socio-technical transformations are characterised by their non-linearities, co-dynamics and high degrees of uncertainty. Non-linearity arises when multiple factors interact and cause and effect are distant in time and space. As described by the authors, complex dynamic systems are mainly characterised by their time behaviour and not by their grade of complicity.

With a focus on large industrial production schemes and power generation facilities, Groesser (2011a and 2012) argues that difficulties in reliably handling dynamic complexity are often the root cause for non-successful project implementations. Remington (2011) and Saynisch (2010) emphasise in the same context of managing complex projects to be mindful of time-driven impact factors and to pay attention to facilitate collaborative problem-solving initiatives. Apart from specific application cases, the authors conclude that working with dynamically complex projects requires the management of continuous learning processes and controlled knowledge formation. As overly simple measures aiming on reducing complexity can be counter-productive, “qualitative feedback modelling” is introduced as the preferred method to effectively deal with dynamic complexity in the framework of strategic management and organisational development (Cooper and Lee, 2009; Groesser, 2011b). Groesser developed “qualitative feedback modelling” based on the use of system dynamic modelling techniques. He stresses that dynamic models and computer simulations play an increasingly important role in individual and group-based decision-making. He underlines that system dynamics modelling provides a reliable basis for achieving sustainable progress in case it is based on cross-boundary knowledge integration. Qualitative feedback modelling is also promoted by Wu, Huang and Liu (2011) who use it for the analysis of the oil price market mechanisms behaviour. They outline in general form that systemic thinking supports the overarching integration of a large number of heterogenic causal relationships formed by high numbers of constituents.

Regarding circular causalities and the need for feedback-driven strategy-finding, Corsatea (2014) describes unidirectional relationships in which private research efforts only respond to policy changes. It is noteworthy that such an approach leaves aside subsequent variations in public policies that are themselves responses to changes in private initiatives. The author examines how the feedback-driven interaction between entrepreneurial initiatives and policy-makers creates opportunities or blocks the development of the technological innovation system. As a result, the need for methods to address circular causalities is formulated. Coordinated interaction of public and private actors is seen as a key factor of success for the governance of a technology development process. The exploration of the interaction between decision-makers and industry representatives is reported to provide useful insight regarding the level of risk faced by the different stakeholders.

According to the International Organization for Standardization (ISO, 2009), the definition of risk is no longer a “chance or probability of loss”, but an “effect of uncertainty on objectives”. Such a deviation from the expected can be either positive or negative. As per this new definition, the risk management process comprises the systematic application of management policies, procedures and practices to the activities of identifying, analysing, evaluating, treating and monitoring risk. The proper management of risk enables an organisation to increase the likelihood of achieving objectives on time and to minimise losses. If capital and resources are allocated efficiently, then planning, prioritisation and decision-making are improved.

As per the Risk and Insurance Management Society (RIMS, 2011), strategic risk management encompasses the interdisciplinary intersection of strategic planning and strategy execution. The methods and techniques applied are “forward looking over the strategic planning time horizon, by using scenario planning for alternate strategy purposes”. They incorporate emerging and dynamic risks, integrate change management for effective response to changing conditions and are strongly linked to the management of capital and funding needs. In this regard, Roberts, Wallace and McClure (2003) underline that strategic risk management mainly focuses on the dynamics in managing risk. Frigo and Anderson (2009) explain that strategic risk management is intended to identify risks that are most critical for achieving the core business objectives. They show that strategic risk management is not a one-time event

but an ongoing circular (i.e. closed-loop) process and emphasise the importance of linking risk assessment and strategy execution. As for the envisaged implementation of 100MW+ marine energy arrays, the efficient interaction between many stakeholders over a long time span is required, standard risk management methods, mainly used in conventional power projects, come to their limits. To enable effective marine energy project implementations, robust strategic risk management routines must form an integral part of stakeholder management policies.

When considering risk management towards an energy system transformation project, the normally applied timeframes and the grade of complexity increase (Söderlund, 2010). The time horizon must be extended towards a strategic dimension, which is generally in the order of five to ten years. Considering the extended time frame, strategic risk management as well as innovation and change processes need to be managed at different time scales and hierarchical levels.

The reviewed literature shows that the multi-level challenges that marine energy faces require the use of dynamic information gathering as well as all-encompassing analyses and evaluation methods. More than two decades ago, Senge (1990) stated in this regard, that most planning tools and analytical methods (at the time) were not equipped to handle dynamic complexity. In between, based on the results of complexity research science and the enormous progress in hard- and software development, better concepts and more powerful tools are available today.

Dealing with feedback-driven and partly circular causalities requires the application of adaptive strategies. This is underlined by Miller et al. (2013) who found in the course of a study on the ecological effects of marine energy development that collaboration between ecologists, industry specialists and government bodies contributes to the goal of reducing the consequences for benthic flora and fauna.

An elementary requirement for successfully managing a complex and dynamic process, either of organisational or technical nature, is to have a clearly defined target, continuous access to reliable feedback information and effective methods to steer. Consequently, the work presented follows an iterative cycle of data gathering, feedback analysis, action planning, implementation of measures and result evaluation as described by Formentini and Romano (2011) in the context of implementing

knowledge transfer practices in the shipbuilding industry. The scope of the research comprises: (i) collection of expert interview data; (ii) data analyses and system dynamics modelling; (iii) calculation of impact factor ranking; and (iv) elaboration of prioritised strategy options for transposition into action plans.

All key elements of a conventional closed-loop control circuit are represented. As such, the concept is re-adjustable to new developments and altering priorities. By the circular process, the development of marine energy can be regularly assessed, strategy options periodically re-adjusted to actual needs and management action plans updated. A repetition rate of several years seems reasonable to support a participative and integrative management strategy.

In the following paragraphs, the characteristics of the methods to represent a system in a software tool are explained, oriented along Forrester (1961) and Kirkwood (1998):

- Causal diagram

Causal diagrams are graphical tools to visualise the structure of a system. They are designed to represent the constituent components and illustrate the interactions between them. The causal links are defined by arrows pointing in the direction of effect. Delays in creating effect between functional elements can be defined.

- Stock and flow diagram

Stock and flow diagrams provide representations that are more rigorous by using further elements, such as stocks, flows, converters, sources and sinks. Complex internal feedback loops and manifold time-related functions can be represented. A detailed and long-term focussed data basis is required to realistically set up and calibrate the corresponding model.

In this research, causal diagrams are used for representing the effectual consequences by individual causes. The resulting impact factor ranking is achieved by calculating the “centre of gravity” in a network consisting of many interlinked constituents. Stocks and flows are not used because of the comparably limited amount of time-correlated data available and the consequential difficulty in realistically configuring non-linear relationships. Building stock and flow diagrams based on data with reduced statistical range regarding short- and long-term dynamics would be vague.



System dynamics is widely used today as a tool to design policies or to identify strategies that contribute to understand the behaviour and improve the performance of a studied system (Oviedo-Ocaña, 2016). In a scientific introduction to apply system dynamics techniques, the trade-off between precise modelling and understandable simplicity is examined whereby preference is generally given to choose the latter (Richardson, 2006). It is outlined that the point is not to create a sophisticated model, but to use system dynamics to start a inspired and substantiated conversations about an examined problem. Considering that models represent a depiction of reality based on simplification, effort must be put in ensuring that the results presented to power market stakeholders are fully substantiated and achieved in a traceable manner.

#### **2.4.4 Advancing marine energy**

Kerr et al. (2014) show that social acceptability is essential to the viability of the marine energy industry and that existing research fails to address many social issues. They report that the lack of trust and transparency along with poor communication are essential factors contributing to the diminishment of stakeholder engagement. Their study confirms that “the absence of detail and consensus on pathways for achieving ambitious deployment targets creates uncertainty in the socio-technical system”. The creation of two-way communication exchanges between stakeholders and the marine energy regulators and decision-makers is described as essential. The authors formulate that such practices are expected to provide social legitimacy and credibility to projects based on community and stakeholder perception.

Corsatea (2014) formulates that positive interaction between technology developers and policy-makers empowers market formation and enables to enhance synergies. The author shows that the top-down formulation of targets has thus far facilitated hesitant progress in the marine energy sector and that an alternative approach involving intermediate levels of decision-making is required. Close cooperation between the authorities in charge of energy policies, researchers and technology developers form part of the technological innovation system (the author prefers the term “innovation mechanism”) and is expected to foster market acceptance.

Focussing on the governance of innovation in the context of the UK energy system transformation, Winskel et al. (2014) emphasise that the elaboration of high-level

guidelines requires the ability to generate a coherent and system-wide perspective. Critical to the development of a technological innovation system is the weak coupling to overall policy ambitions, organisational fragmentation and lacking transparency of the interweaving of public and private interests, they formulate. In the same context, Del Río and Bleda (2012) warn that in the absence of coordinated plans and poor networking between industry and decision-makers in the renewable energy sector, a blocking mechanism with respect to legitimacy might emerge.

It remains to be noted that most relevant literature concentrating on stakeholder-wide balanced strategy options was published after defining the present research topic. The decision to orientate the research into this direction was taken in March 2011 and is now supported by augmenting activities in the field and the increasing number of scientific publications on stakeholder-driven marine energy strategy-finding. A number of publically funding research activities (initiated by SI Ocean and the European Commission) now investigate into the same direction.

## **2.5 Inter-organisational learning and strategic partnerships**

Lhuillery and Pfister (2009) examined the determinants of failures with negative impact on the innovation performance in industry R&D collaboration. Although such partnerships often improve corporate performance on average, statistical evidence reveals that a significant share of them fail to meet their objectives. The authors explored which firm-level characteristics increase the risk that a joint innovation project is delayed or stopped<sup>18</sup>. Bouncken and Kraus (2013) apply the term “co-opetition” as a simultaneous pursuit of cooperation and competition. In the context of supply chain partnerships, Zhang and Frazier (2011) found that co-opetition is often used as a short-term strategy for firms to achieve certain goals. In their contribution, Doorley (1993) is cited, who detected that from 880 examined alliances 60% had a 4-year survival rate while less than 20% remained in place for ten years. Stiles (1995) analysed global collaborative partnerships and reports that 50% are deemed as failures, not realising their full potential due to deficits in management skills and expertise.

---

<sup>18</sup> The study indicates that 14% of R&D collaborating firms had to abandon or delay their innovation projects due to difficulties in their partnerships. Particularly firms collaborating with their suppliers face a high risk of cooperation failures.

The term “competitive collaboration” was introduced by Hamel, Doz and Prahalad (1989) for strategic alliances between two or more competing firms that interact to pursue a set of agreed goals in one or more key strategic areas, as formulated by Yoshino and Rangan (1995). “Pre-competitive collaboration” is a term used by Weber (2005) that refers to when “competitors share early stages of research that benefit all”. Hull and Slowinski (1990) demonstrate that cooperative relationships in high technology segments between large industrial conglomerates (with strong market positions) and small firms (providing innovative technology) brought in-demand products to market that neither firm alone could have accomplished. Gnyawali and Park (2011) describe the co-opetition between Samsung Electronics and Sony Corporation advanced innovation in LCD panel technology. They underline that co-opetition is very helpful for firms to address major technological challenges and to advance innovation. The potential to develop integrative technologies and to create new markets is improved. The research of Bouncken and Kraus (2013) on competitive collaboration in knowledge-intensive industries is based on the analysis of 830 small and medium-sized enterprises operating in inter-firm alliances and clusters to share R&D. The main finding of this empirical study is that co-opetition negatively affects extremely novel revolutionary innovation (that changes existing technologies or makes them obsolete) while it triggers radical innovation (i.e. a technological breakthrough as in marine energy). Ritala and Hurmelinna-Laukkanen (2009) analysed how to create value in high-tech industry sectors by innovation-related co-opetition. They conclude that the positive effect of a common knowledge base on value-creation is stronger in case of incremental innovation (i.e. a series of small improvements or upgrades to existing products or services) than for radical innovation.

Håkansson (1990) underlines that collaborative relationships are of strategic importance to innovation-driving companies but underlines that considerable investment is required to establish and maintain cooperation until the partners can derive benefit from it. He describes that collaborative relationships generally evolve organically and that the starting point is often an already established relationship where mutual trust has developed. The author emphasises that it can be problematic to plan joint activities to any greater degree, especially if the planning model is overly simple or rigid.

## **2.6 Complicacy and complexity**

### **2.6.1 General**

There is a noticeable increase of complexity in today's world comprising the fields of technology, economy, policy and society. For successful navigation in increasingly demanding and non-transparent environments, high-level analytical skills and strategic talent for taking adequate action to achieve sustainable success are required.

A key finding in a comprehensive study on confronting complexity in business is that “companies need to be agile to cut through the layers of complexity and to achieve growth” (KPMG, 2011). As a way of dealing with novel and complex tasks, Swinth (1971) proposes “joint problem-solving” which requires a common goal-orientation, the definition of an overall consistent set of actions and the linkage of organisational centres. In an inductive study on product innovation in continuously changing organisations, Brown and Eisenhardt (1997) proclaim the importance of extensive communication and design freedom to create improvisation within projects. They consider such processes as forming complex adaptive systems and point out that firms which are successful in innovation rely on experimental products and strategic alliances.

Studies in the field of system dynamics revealed that in conventional management mainly aspects of detail complexity are considered, but that “the real leverage lies in understanding dynamic complexity” (Sterman, 2010). Atkinson et al. (2006) formulate that in an innovative environment, where flexibility and tolerance of vagueness are indispensable, a “higher level of abstraction” is required. They found that common project management does apply “uncertainty reduction” (i.e. complexity reduction), but does not address “uncertainty management” (i.e. managing dynamic complexity), particularly required in projects highly subject to external influences. Senge (1990) underlines, from an adaptive learning perspective, that most planning tools and analytical methods are not equipped to handle dynamic complexity.

In the course of a technology convergence process, a project can change its principal characteristics. In aviation history, as exemplarily described by Ahern and Leavy (2014), aircraft design progressed from being a complex project (when the technology was poorly understood) to a complicated project (when detailed designs are

documented for production assembly). In contrast, as described by Snowden (2002), a one-off project may not transition from being complex to becoming complicated until it is delivered and retrospectively comprehended in its entirety.

In the academic literature on complexity research, the fundamental difference between detail and dynamic complexity is underlined (Schwaninger, 2009a; Sterman, 1994). After separating detail-complex tasks from issues pertaining to dynamic complexity, a better understanding of the nature of a problem is gained.

### **2.6.2 Detail (or combinatorial) complexity**

Detail or combinatorial complexity is characterised by many interdependent elements and a large number of combinatorial possibilities. The respective tasks comprise a high level of complicity.

Apart from technology-related questions, detail complexity also appears within stakeholder-internal business management and in tasks of an organisational nature. By definition, detail-complex problems or projects can be completely specified in advance and handled by the application of prior knowledge, skills and tools. A simplified formula to describe the level detail complexity ( $V$ ) is to raise the number of potential states of each element ( $z$ ) by an exponent ( $n$ ) representing the number of elements, leading to  $V = z^n$ . The formula is not adequate to calculate dynamic complexity (Schwaninger, 2009b).

### **2.6.3 Dynamic complexity**

Even in simple systems with low combinatorial diversity, dynamic complexity can arise. It often shows aspects of counter-intuitive behaviour (Sterman, 2001; Sterman, 2002; Sterman and Booth Sweeney, 2002). Cause and effect can be subtle and obvious interventions can produce non-obvious consequences (Sterman, 1992).

Dynamic complexity is a characteristic of large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships with accumulation or delay functions and the need to integrate hard and soft data (Cooper and Lee, 2009). Complexity science examines dynamical properties like self-organisation, adaptation and emergence. In the course of working in dynamically complex projects, continuous learning and knowledge formation are paramount. Engwall (1998) formulates this

within a project management context by saying that it is necessary to continuously create knowledge over the project life cycle. Aspects of dynamic complexity require long-term regular observation and cautiously defined intervention measures.

## **2.7 Chapter summary**

Based on the findings in the literature review, important tasks to be addressed are:

- To analyse and interrupt the circular relationship between reliability and funding to create investor confidence and to work on reaching cost competitiveness.
- To elaborate stakeholder-wide balanced strategies to de-risk pilot deployments because significant technological barriers, high capital requirements and the uncertainty of future revenues hindering the development of the sector.
- To mitigate the tendency for entrepreneurs to compete in very initial stages with each other instead of forming coalitions and inter-firm alliances.
- To examine the possibility to shift high-risk phases to early project stages in the course of implementing demonstrations.

In the current literature, the difficulties the sector faces are described and investor restraint is made evident. Although ideas for advancing the technology and improving the investment climate are described, the presentation of a conclusive set of measures to advance commercialisation of the sector is missing. Well-founded arguments and coordinated strategies to work stepwise towards market acceptance are not presented.

The identified gap in literature is addressed in the present research by:

- The elaboration of a practically relevant strategy-finding method based on the unbiased and transparent integration of cross-category stakeholder knowledge.
- The identification of stakeholder-specific prioritised strategy options for direct application in action plans.
- The provision of arguments for improving knowledge sharing and collaboration.

### **3 METHOD AND MATERIALS**

The research is designed for the purpose to formulate long-term effective strategies for commercialising marine energy. The method is based on empirically-obtained expert data which is considered as elementary for generating credible results and for issuing impartial recommendations. The materials used are chosen to allow the prediction of effective strategies by high quality data analytics. The identification of hidden correlations in the heterogeneous set of data supports the acceleration of the maturation process and substantiates tactical management decision.

In this chapter, the basic characteristics of the strategy-finding process are explained and the reason for selecting system dynamics modelling is explained. Furthermore, the preparation of the interview series and the composition of the questionnaire are described.

#### **3.1 Research design**

The marine energy maturation and commercialisation process is characterised by serious technical and organisational challenges, extraordinary funding requirements, a considerable public awareness and a long-term orientation. The successful handling of such a comprehensive and demanding task requires the integration of a great variety of stakeholder interests and constraints.

As there was no limiting specification, no predefined target nor any third party interest in principally directing this research, a truly holistic approach could be chosen to form the foundation of the work. With the aim to generate a new understanding of the prevalent risk complexes hindering the commercialisation of marine energy, the interviewing process was designed towards having an open-integrative rather than a detailed-specialist character. Consequently, for the present research, managers, experts scientists and specialists from all organisations actively involved in marine energy were invited to contribute with their experience, knowledge and opinion.

A basic principle applied in this research is to create new insight by compiling different sources of knowledge for the elaboration of an optimum strategy towards achieving market competitive generation. To be able to adapt to a continuously changing socio-technical environment, evolutionary steering mechanisms and systemic thinking are

required. A successful strategy must be flexible and re-adjustable to upcoming trends and changing priorities.

In Appendix B.1 the fundamental idea behind the present concept, i.e. the holistic risk complex analysis by stakeholder-wide data acquisition is represented in graphical form. For each stakeholder group (vertical axis), one pictured horizontal layer symbolises an averaged risk chart in which pre-defined risk types (x-axis) are related to consecutive project stages (y-axis). Individual risk levels on the averaged risk chart are represented by colour-coded fields (green for low, yellow for mid and red for high). The figure was designed to explain to the interviewees the holistic concept behind the research with the aim to achieve replies of high adequacy and quality. Even as it was intended to fill the averaged risk charts with field data, due to the statistically relatively low number of conducted interviews, an informative image could not be generated. By superimposing multiple risk layers, cross-cutting themes and hidden interdependencies would have become detectable as so-called trans-organisational risk complexes.

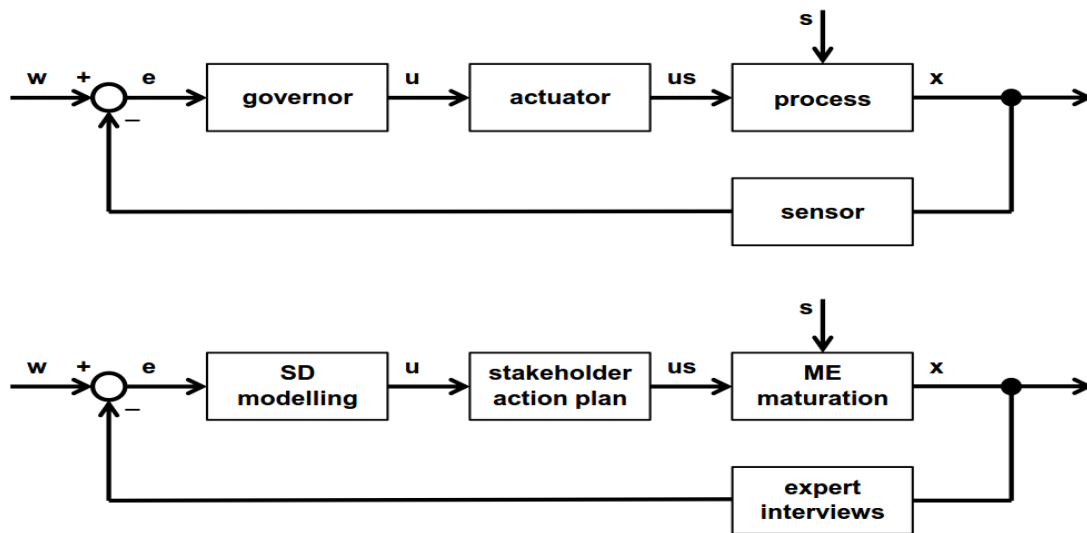
Independent of the graphical representation, of special interest are transition periods between project stages and interfacing areas between different risk-owners. As an example, the immediate responsibility for the economic viability of a marine energy project, mainly determined by the investment and the profit by selling electricity, is variously transferred between stakeholders and modified with regard to accuracy and quality. Examining such processes provides potential for de-risking the sector.

### **3.2 Analogy to closed-loop control concept**

Systems dynamics arises from control theory. Fig. 3 shows one standard and one adapted closed loop block diagram comprising all functional elements defining a technological or organisational process to be managed.

The respective analogies between the terms and concepts in control theory and the concept behind the process of managing the marine energy commercialisation are shown in Table 2.





**Fig. 3: Closed-loop diagrams: Standard terms (top) & adaptations (bottom)**

The reference value or target factor (“w”) is to achieve market competitive electricity generation by marine energy (see Appendix B.2 – Question 5). Feedback on the present status of the maturation and commercialisation process is gained by expert interviews (“sensor”). Based on the identified deficiencies and weaknesses the sector suffers (“e” for error), impact or top-level driving factors and prioritised strategy options (“u”) are formulated. Subsequently, they are assessed and executed by the management of the stakeholders in the form of action plans (“us”). As the socio-technical environment in which marine energy arises is highly challenging and dynamically changing (“s”), the maturation process is permanently influenced (“disturbed”). This can be either positive (supporting) or negative (hindering) which affects the development trajectory of the sector (“x”) and thus the achievement of the envisaged market acceptance.

**Table 2: Analogies of terms in control theory and the research context**

Control theory	Marine energy commercialisation
Reference value $w$	Target: “Full-commercial power generation by marine energy”
Control deviation $e$	Remaining development and commercialisation progress
Governor	System dynamics (SD) modelling and analysis
Actuating signal $u$	Identified impact factors and prioritised strategy options
Actuator	Stakeholder executives’ assessment of strategy options
Actuating value $us$	Stakeholder executives’ action plan (directives and instructions)
Process	Marine energy (ME) maturation and commercialisation
Disturbance $s$	Setbacks, difficulties, risk impact
Actual value $x$	Unbiased image of the present status of the marine energy sector
Sensor (feedback element)	Periodic cross-category expert interviews

### **3.3 Preparation of survey and data acquisition**

#### **3.3.1 Definition of target group and expectations**

In line with the principles applied in grounded theory, a non-restricted (expert) group of interviewees was invited to contribute the fundamental input required to create new knowledge. The goal was to approach highly qualified individuals, with a great breadth and depth of knowledge in the field. The complete spectrum of stakeholders active in marine energy was considered in the course of setting up the interviewing process. Most diverse stakeholder groups were contacted ranging from governmental authorities to NGOs, from device manufacturers to certification bodies, from investors to operators, from academia to consultancies and from the offshore wind to the oil & gas industry. Within the context of the research, the contacted interview participants represent a very heterogeneous group.

The interviews were prepared with the intention of gaining a wide-ranging understanding of the characteristics and difficulties of presently ongoing and planned marine energy activities. A further interest was in examining inter-organisational blockages and stereotype risk mechanisms. The goal was to analyse and contrast the reported singular-case problems in order to identify universal factors.

The stipulation from the literature review was that the transposition of knowledge from a wide spectrum of stakeholders is key for forming an overarching strategy concept. Away from stakeholder-internal risk assessment routines mainly focussing on defined criteria (e.g. cost, staffing, technology), in this research an all-encompassing approach is applied. This was consecutively confirmed when considering the inhomogeneity of the interview replies and the diverging internal targets of stakeholders. For example, none of the interviewees mentioned the need to rapidly achieve market breakthrough, for which a temporarily increased level of cooperation between competitors might be helpful. This was only found out by applying integrative data analytics. Furthermore, it was confirmed that external stakeholders (in this perspective policy-makers and funding bodies) partly direct their resources towards tackling barriers other than the ones the industry immediately faced.

In line with the outcome of the literature review, the high capital requirements and the uncertainty of future revenues are mainly hindering to the development of the marine

energy sector. Consistent with the findings by Negro, Alkemade and Hekkert (2012), early competition and commercial pressure were identified as blocking cooperative interaction. Another important parallel to the reviewed literature was found in the significance given to systems thinking and the application of systems engineering principles. For example, the benefits by applying a whole-system evaluation approach and system-level optimisation techniques were mentioned by a device manufacturer executive.

Taking into account the grade of novelty and the pace of change in the global renewable energy market, there is no real alternative than to approach the key players in the sector in order to get first-hand insight by bilateral interviews. Essential developments take place so quickly that referencing to scholarly literature or conference proceeding can only serve for analysing averaged tendencies or global developments. As the aim of the thesis is to create relevant and practically applicable strategic knowledge on how to resolve the major risk complexes hindering the commercialisation, direct access to latest high-level expert information is decisive.

### **3.3.2 Sampling strategy**

The recruitment of interview participants can be realised according to Wilson (2013) by quota sampling (participants relative to a proportion), dimensional sampling (participant who fit the critical dimension of the study), convenience sample (anyone who meets basic screening criteria), purposive sampling (selection by qualification), snowball sampling (an excellent interviewee is asked to name other participants), extreme sampling (only people with exceptional or non-traditional knowledge) and heterogeneous sampling (widest range of people possible).

The selection strategy applied in this study is a combination of quota sampling, purposive and snowball sampling. This is because the survey covers a field for which years of in-depth experience are required to be in the position to answer in a qualified manner and consecutively received recommendations for further interviewees to be invited. Due to the approach of inviting all stakeholder groups to contribute with their expertise to the data set used for the configuration of the system dynamics models, a compromise between the depth of interview information and the formally structured comparability of content is required.

### 3.3.3 Interview type

Attwater and Hase (2013) and Dick (1998) describe four main interview types:

- Structured interview: The interviewer asks a previously prepared set of questions in a standardised manner to collect uniform data. As the order of questions is fixed, all are answered within the same context, which minimises context effects.
- Semi-structured interview: The interviewer has a framework of themes to be explored but new ideas can be brought up as a result of what the interviewee says. Based on a guide with an informal grouping of topics and questions, the interviewer can ask different participants in different ways.
- Unstructured interview: This type of interview does not follow a predetermined list of questions. The interview questions emerge over time and during the interview process.
- Convergent interview: Convergent interviews allow the collecting a greater depth of data than other types. After a pair of interviews, the themes that emerged are compared. If informants agreed on one theme, in later interviews, diverging views are of highest interest. If the interviewees disagreed about some topic, a further interview series probes for an explanation.

Under consideration of the timeframe and the difficulties in obtaining high-level interview appointments, the semi-structured interview type was selected. This type is widely used in qualitative research in social sciences and best fits to the present research intention. In the course of the interviews, the best benefit was taken from working along the questionnaire but allowing less productive questions to be omitted and to focus on individual highlights and knowledge. The interview replies were not transcribed but precisely transferred to a workable uniform database.

### 3.3.4 Questionnaire

For the empirical data collection, an introductory document and a questionnaire with 90 questions was developed. 48 were YES/NO questions and 42 of a qualitative character, referring to stakeholder-related experience. Background information to orientate the interviewees and the 4-page questionnaire can be found in Appendix B.2.

### **3.3.5 Participating stakeholders**

After contacting 140 pre-selected representatives from 15 stakeholder groups, 71 sets of feedback were received. Of these 11 were face-to-face interviews, 15 telephone interviews as well as 20 filled-out questionnaires. Although 2 questionnaires had to be discarded because they were largely incomplete, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was retained for the analysis. This corresponds to an effective return rate of 31.4%, which is more than the usual number for studies of this nature (Masini and Menichetti, 2012).

Examples for the professional status of the interview partners are: CEO, Chief Scientist, Communications Director, Head of Business Development, Marine Spatial Planning Theme Leader, Professor, Programme Director, Research & Project Coordinator, Senior Principal Surveyor, Strategy Manager, Technical Director for Wave and Tidal, Test Site Coordinator, Vice President Energy Department). For details, please refer to Table 3 and Appendix C.1.

A total of 2,617 individual replies to all questions had to be analysed and grouped in order to formulate higher-level correlations serving as input data to the three system dynamics models.

The single person interviews were conducted between June 2012 and April 2013 either face-to-face at the premises of the interviewee, by telephone or in writing by filling out the questionnaire. In order to respect the tight time schedules of the participants, the duration of the interviews was adapted according to requirements to be between 20 and 90 minutes. In the course of preparing the interviewees, the participants were informed that their data would be used in an anonymised form for the research and their organisation name would be published. Furthermore, the intention of the research was described in such a manner that a key interest is to analyse and improve the interaction between the different stakeholder groups. Consequently, the participants acted in their official role as representative for their organisation and replied accordingly. As such, parts of the questionnaire that were critical to some stakeholders were not filled out. In some cases, especially in face-to-face interviews, personal assessments or opinions were discussed but not protocolled.

**Table 3: List of interview participants**

<b>Stakeholder group</b>	<b>Stakeholder</b>	<b>Country</b>
Government (associations) & trade organisation	The Scottish Government	UK
	Marine Scotland	UK
	Energy Technologies Institute	UK
	Carbon Trust	UK
	Department of Energy & Climate Change	UK
	The Crown Estate	UK
	Scottish Natural Heritage	UK
	Centre for Environment, Fisheries, Aquaculture	UK
	RenewableUK	UK
	Technology Strategy Board (Innovate UK)	UK
Certifying authorities	Det Norske Veritas	Norway
	Lloyd's Register	UK
Investors & lenders	Green Giraffe	UK
Insurance companies & law firm	Eversheds International	UK
Academia & research	University of Washington	USA
	University of Edinburgh (2x)	UK
	National Taiwan Ocean University	Taiwan
	Irish Marine Institute	Ireland
Engineering consultancies	Natural Power	UK
	Xodus Group	UK
	Tecnia Research & Innovation	Spain
	South West Renewable Energy Agency	UK
	Royal Haskoning	UK
Project developers	Emera	Canada
	EDF	France
	Electricity Supply Board	Ireland
	Iberdrola	Spain
Owners & operators	ScottishPower Renewables	UK
	Ente Vasco de la Energía	Spain
Transmission system owners	SSE	UK
Device manufacturers	Marine Current Turbines	UK
	Pelamis Wave Power	UK
	Wavebob	Ireland
	Siemens	Germany
	Wave Star	Denmark
	Ocean Renewable Power Company	USA
Offshore contractors	6 contacted (no feedback received)	-
Test site operators	European Marine Energy Centre	UK
	Fundy Ocean Research Centre for Energy	Canada
	National Renewable Energy Centre	UK
	Minas Basin Pulp and Power	Canada
	France Energies Marines	France
NGOs	Greenpeace	UK
Offshore wind industry	Dong Energy Power	UK
Oil & gas industry	4 contacted (no feedback received)	-

It was found that there was no statistical significance between the data received as feedback by personal interviews, the phone survey or the filled-out questionnaires. As for the research, the flexibility to either conduct interviews or exchange written information was required. Attention was given to uniformly ensuring the information gathering followed the detailed questionnaire. In the course of preparing and scheduling the personal and telephone interviews, the participants received the questionnaire and background file in a timely manner so that the basis of the interaction was well defined.

As detailed in Appendix C.2, the number of respondents per questions varies between 12 and 42. Critical questions touching company policies and reputation, such as key risks, cost increases or difficulties reaching internal targets received sparse responses. For the crucial Question 5, feedback from 42 respondents were received. The two interviewees that did not reply to this question explained this was due to time constraints.

### **3.3.6 How many interviews are enough?**

The aim of the interviews is to identify relevant themes, beliefs and practices for preparing a quantitative analysis. The high-profile group of individuals contacted, i.e. a sub-population of all individuals working in the marine energy sector, forms the statistical population size.

While the list of participants might suggest that the population was intended to represent the “Atlantic Arc”, the geographical focus of the research was limited to the UK and Ireland. The corresponding 30 interviews were conducted in the UK and Ireland. Additional interview data were gained in countries like Canada, Denmark, France, Germany, Norway, Spain, Taiwan and USA, totalling 14 interviews.

At the time of starting the interviews in 2012, Britain was home to about 35 of the world’s 120 to 130 tidal stream and wave device developers (Macalister, 2011). According to Davidson (2016) the fledgling marine energy industry already supports 1,700 jobs across the UK. Referring to Ireland, a 2011 paper by the Marine Renewables Industry Association (MRIA, 2011), stated that a total of 191 people (121 in universities, 68 in industry and 2 in agencies) work in ocean energy R&D, accounting for the bulk of those engaged with the sector.

Based on above data, the statistical overall population size is estimated for the two countries as 1,900 (for the UK 1,700 and for Ireland about 200). In order to determine the size of the population used for the analysis, it is assumed that every tenth person working in the sector has sufficient seniority to comply with the requirements of the high-level qualitative interview approach of the survey, leading to a value of 190. This is reflected by the job titles of the interview participants contacted (Appendix C.1), e.g., CEO, Director, Programme Manager, Strategy Manager, Head of Team, Partner, Professor and Government Advisor.

Regarding the population size of 190, the following analysis examined if the 30 respondents from the UK and Ireland represented a sufficiently large sample size according to standard statistical calculations for mass survey. Equation 1 serves to determine the required sample size ( $S$ ) under consideration of population sizes, confidence levels, bias of percentage values and error margins.

$$S = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left( \frac{z^2 \times p(1-p)}{e^2 \times N} \right)} \quad \text{Equation 1}$$

The values shown in Table 4 serve as initial data for Equation 1.

**Table 4: Input data for standard sample size calculation**

Variable	Definition	Value
$z$	The <u>z-score</u> is the number of standard deviations a given proportion is away from the mean. The underlying confidence level defines the probability that a value will fall between the upper and lower bound of the probability distribution. The correlation between the confidence level and the z-score (in parenthesis) is 80% (1.28), 85% (1.44), 90% (1.65), 95% (1.96) and 99% (2.58). Common values are 99%, 95% and 90%. In this first calculation, a confidence level of 95% is chosen.	1.96
$p$	Where a survey is conducted for the first time and contains more than one question the <u>percentage value</u> is best set at 50%. As such, any bias is avoided.	0.50
$e$	The <u>margin of error</u> defines how much the survey results are expected to reflect the views of the overall population. 10% is a usual value.	0.10
$N$	The <u>population</u> is the entire pool from which a statistical sample is drawn. The number of 190 was defined in the paragraph above.	190



Entering these values leads to the determination of the minimum sample size needed:

$$S = \frac{\frac{1.96^2 \times 0.50 (1 - 0.50)}{0.10^2}}{1 + \left( \frac{1.96^2 \times 0.50 (1 - 0.50)}{0.10^2 \times 190} \right)}$$

$$S = 64$$

The value of 64 is significantly above the performed 30 interviews. However, as the group of interviewees is homogenous with regard to their capability to reply to the posed questions, the confidence level requirement is reduced from 95 to 90% (z-score now 1.65) which means that one time in ten, an outlier will be found. The margin of error is set to 14% (instead of 10%).

$$S = \frac{\frac{1.65^2 \times 0.50 (1 - 0.50)}{0.14^2}}{1 + \left( \frac{1.65^2 \times 0.50 (1 - 0.50)}{0.14^2 \times 190} \right)}$$

$$S = 29$$

Based on the adapted input data that unavoidably lead to a greater degree of uncertainty, the calculated minimum required sample size of 29 confirms the number of interviews conducted to be adequate. The used statistical formula reflect standard statistics used in quantitative research in the course of consumer product market research or other large sample number surveys.

Sutton and Austin (2015) investigate reliability in the interpretation and representation of interview data used in qualitative research. In contrast to quantitative research, there are no statistical tests available to verify the reliability and validity of the findings. Lincoln and Guba (1985) introduce the term “trustworthiness” for verifying the credibility, transferability and confirmability of the findings. They describe a series of techniques that can be used to verify qualitative research for example by prolonged engagement, peer debriefing, negative case analysis and triangulation<sup>19</sup>.

---

<sup>19</sup> Triangulation is a powerful technique used in social sciences that facilitates validation of data through cross verification from two or more sources. By combining multiple theories, methods and empirical materials, it is expected to overcome the intrinsic biases that come from single method and single-theory qualitative studies.

Given the specific characteristics of qualitative surveys around highly specialist topics (like the commercialisation of marine energy) with unavoidably lower numbers of respondents, recent scientific contributions have been published. The main characteristics and formula used in this context are summarised below.

Galvin (2015) considers the reliability of energy research using small samples of interviews to identify themes, beliefs, practices or other phenomena. In the course of defining the minimum number of required interviews, it is explained that in most empirical studies a saturation of replies is achieved after 12 and definitively after 30 interviews. The author presents formula to determine the minimum required number of interviews ( $n$ ) to reliably detect themes that are in discussion by a minority (Equation 2) and on the other hand the proportionate level at which an issue needs to be represented in the population in order to emerge in the interviews (Equation 3).

$$n = \frac{\ln(1 - P)}{\ln(1 - R)} \quad \text{Equation 2}$$

The values shown in Table 5 serve as entry data for Equation 2.

**Table 5: Input data for qualitative research sample size calculation**

Variable	Definition	Value
$P$	The <u>confidence level</u> defines the probability that a value will fall between the upper and lower bound of the probability distribution. In this calculation, a value of 95% is chosen.	0.95
$R$	The defined <u>proportion of the population</u> , which holds relevant themes, beliefs and practices. In this calculation, a value of 10% is chosen.	0.10
$n$	The <u>number of interviews</u> conducted with participants from UK and Ireland.	30

Entering these values leads to the determination of the minimum number of interviews required (with a certain confidence level) that all relevant themes, beliefs and practices, which are held by a defined proportion of the population, will occur within the interview sample:

$$n = \frac{\ln(1 - 0.95)}{\ln(1 - 0.10)}$$

$$n = 28.4$$

To ensure at 95% confidence that the specific themes held by 10% or more of the population, a minimum number of 29 interviews is required.

Equation 3 allows a cross-check of the results as, with this formula, the proportionate level at which an issue needs to be represented in the population in order to emerge in the defined number of interviews at 95% confidence level can be calculated using the data from Table 5.

$$R = 1 - \sqrt[n]{(1 - P)} \quad \text{Equation 3}$$

$$R = 1 - \sqrt[30]{(1 - 0.95)}$$

$$R = 9.5$$

In the UK/Ireland-focussed research in this thesis, the 30 conducted interviews provide 95% confidence that a topic is detected even when it is only supported by 10% of the population. In order to create realistic causal diagrams, it is equally important to consider topics with minor statistical relevance (i.e. held by only 10% of the population). Finally, the overall relevance of a topic on the final target is defined to be the impact strength values between the generic terms and the correlated functional elements.

Trotter and Schensul (1998) as cited by Guest, Bunce and Johnson (2006) underline that in theory, all research should use a probabilistic sampling methodology, but in practice, it is virtually impossible to do so in the field. Research that is field-oriented and not concerned with statistical generalizability often uses non-probabilistic samples. The most commonly used samples, particularly in applied research, are purposive, i.e. selection of interviewees by qualification.

Morse (1995) observed that saturation is key to excellent qualitative work. He noted that there were no published guidelines or tests of adequacy for estimating the sample size required to reach saturation. As saturation is considered as standard by which purposive sample sizes are determined, Guest, Bunce and Johnson (2006) underline the general need for such a numerical guideline.

Morse (1994) recommends at least 6 participants for phenomenological studies (that attempt to understand people's perceptions, perspectives and understandings of a

particular situation or phenomenon) and approximately 35 for grounded theory studies (to which the present research can be associated with, as outlined in the literature section). Creswell (1998) recommends between 5 and 25 interviews for phenomenological studies and 25 for grounded theory studies. Guest, Bunce and Johnson (2006) quote Bertaux (1981) who argues that 15 is the smallest acceptable sample size in qualitative research.

### 3.3.7 Stakeholder over- and under-representation

When analysing the number and distribution of the respondents shown in Appendix C.1, an over- and under-representation of specific stakeholder groups can be detected as shown in Table 6. The group of device manufacturers leads with 30 interview requests (21%) of contacted stakeholder groups, followed by Government (associations) & trade organisation (16%), academia & research (13%) and engineering consultancies (9%). The further stakeholder groups received significantly fewer invitations (between 6 and 2%).

**Table 6: Analysis of stakeholder-specific ratio contacted to feedback**

Stakeholder group	Randomly contacted (1)		Feedback received (2)		% -ratio (2) / (1)	Trend by ratio
	[abs.]	[%]	[abs.]	[%]		
Government (associations) & trade organisation	22	<b>16</b>	10	<b>23</b>	<b>1.4</b>	↑
Certifying authorities	4	<b>3</b>	2	<b>5</b>	<b>1.6</b>	↑ ↑
Investors & lenders	5	<b>4</b>	1	<b>2</b>	<b>0.6</b>	↓ ↓
Insurance companies & law firm	5	<b>4</b>	1	<b>2</b>	<b>0.6</b>	↓ ↓
Academia & research	18	<b>13</b>	5	<b>11</b>	<b>0.9</b>	↔
Engineering consultancies	12	<b>9</b>	5	<b>11</b>	<b>1.3</b>	↑
Project developers	8	<b>6</b>	4	<b>9</b>	<b>1.6</b>	↑ ↑
Owners & operators	6	<b>4</b>	2	<b>5</b>	<b>1.1</b>	↔
Transmission system owners	5	<b>4</b>	1	<b>2</b>	<b>0.6</b>	↓ ↓
Device manufacturers	30	<b>21</b>	6	<b>14</b>	<b>0.6</b>	↓ ↓
Offshore contractors	6	<b>4</b>	0	<b>0</b>	<b>0.0</b>	n.a.
Test site operators	8	<b>6</b>	5	<b>11</b>	<b>2.0</b>	↑ ↑ ↑
NGOs	3	<b>2</b>	1	<b>2</b>	<b>1.1</b>	↔
Offshore wind industry	4	<b>3</b>	1	<b>2</b>	<b>0.8</b>	↓
Oil & gas industry	4	<b>3</b>	0	<b>0</b>	<b>0.0</b>	n.a.
Total	140	<b>100</b>	44	<b>100</b>	-	-

In column “Trend by ratio”, the allocated rank of each considered generic term is classified by comparing it to the SD-model 1 percentage values (↔ stands for a practically identical distribution of  $\pm 0.1$  and each single arrow for  $\pm 0.3$  ratio change).

The basic sampling strategy applied in this research is purposive, i.e. by selection according to qualification. In the course of the initial identification and determination of potential interview participants several sources were used: (i) personal recommendations from the supervisory team (as contacting high-level representatives is difficult without a personal contact); (ii) marine energy conference participant lists and keynote speakers; (iii) social media networks; and (iv) press releases. Although the preparation of the interviews took about one year, it was necessary to limit selection of participants at a certain stage, given the time restrictions. After the first interviews, further high-profile candidates were identified as per the snowball sampling concept.

As shown in Appendix B.1, stakeholder-wide data acquisition covering all project stages forms the basis of the applied holistic and non-limiting research concept. Where the main criteria concerning the professional qualification was fulfilled, no further pre-selection of interview participants was used, avoiding any unnecessary initial bias. However, the feedback received does not follow one-to-one the initial distribution of contacted stakeholders. Originally, for example, the group of government (associations) & trade organisation represented 16% of all stakeholders contacted, but 23% of the total feedback received, leading to a 1.4 factor of over-proportional representation. In Table 6, this shift in ranking is reflected in the two columns “%-ratio (2) / (1)” and “Trend by ratio”. Some stakeholders become over- and others under-represented compared to the original distribution as per the invitations to participate.

- Over-proportionally represented stakeholders: Test site operators with %-ratio of 2.0 (the group represents 6% of all stakeholder groups contacted by represents 11% of the feedback received) lead this group, followed by certifying authorities and project developers (1.6, each), government (associations) & trade organisation (1.4) and engineering consultancies (1.3). Owners & operators and NGOs are only slightly over-represented (1.1, each).
- Under-proportionally represented stakeholders: Apart from stakeholder groups from which no feedback was received (offshore contractors and the oil & gas industry), the ranking of the under-represented groups is led by the investors & lenders, insurance companies & law firm, transmission system owners and device manufacturers (0.6, each). A slightly lower level of under-representation was achieved by the offshore wind industry (0.8) and academia and research (0.9).

The varying ratio values between the number of interview requests submitted and the responses received, causing the over- or under-representation of stakeholder groups, is explained by the following:

- Significant statistical error potential given the small number of persons contacted per stakeholder groups (with a minimum value of only 3).
- Immature nature of the industry and correlated limited business experience.
- Relevance of the marine energy sector for company targets regarding sales and earnings (especially for test site operators and certifying authorities directly profiting from the sector as it is today) and public organisations' strategic goals.
- Cautiousness of device manufacturers with respect to communicating details and qualitative assessments because of negative press caused by setbacks and unrealistic assumptions on the pace of progress and technology readiness.
- Different levels of experience regarding marketing, public relations and interaction with academia due to differing business models or official bodies' duties.

Considering the high feedback ratios by test site operators and certifying authorities, an over-optimistic situational assessment might be created as these stakeholders directly profit from the sector at the time. On the other side of the scale, we see an under-representation of increasingly restrained stakeholders that have experienced considerable setbacks in the past.

Regarding the different level of detail provided on different responses, it has to be kept in mind that the feedback was received in the course of 11 personal and 15 telephone interviews as well as 18 questionnaires completed remotely by the respondent. Interview, either personal or by telephone allow more in-depth information gathering closer to the principle of convergent interviews. Personal experience of themes that emerged during the discussions could be deepened as required. Nevertheless, all interviews were conducted strictly along the questionnaire, submitted weeks before so that the respondent could prepare.

### **3.4 Data analytics and selection of software tool**

A central issue in the course of setting up the research was to identify a powerful tool that guarantees the traceable analysis of multi-dimensional expert interview data. A key requirement was the suitability for the present research case and a functionality that allows examining in more detail where necessary. In the following, potential approaches and corresponding software solutions that were evaluated are described.

#### **3.4.1 Bayesian belief network**

Bayesian belief networks (BBN) were first developed at Stanford University in the 1970s. They describe cause-effect relationships among variables through graphical models. BBNs consist of nodes (representing variables of the domain) and arcs (representing dependence relationships between the nodes). The networks are based on conditional probability theory and are often used for predicting the probability of events and for representing uncertain knowledge about causal and associational relations among variables (Luu, 2009). They provide great flexibility in their capacity for accepting cross-category input data (Attoh-Okine, 2002).

#### **3.4.2 Statistical package for the social sciences**

The statistical package for the social sciences (SPSS) is a commercial program for statistical analysis widely used by market researchers, survey companies, education researchers and data miners. SPSS places constraints on the internal file structure, data types, data processing and matching files. A functionally identical freeware alternative is known under PSPP, which has no acronymic expansion.

#### **3.4.3 Big data analytics**

Big data analytics allow examining millions of combinations between thousands of operating variables in a complex system. The goal is to identify the most influencing correlations and to determine the setting of variables that demonstrate a desired optimum system performance. Valuable management-level information can be gained by automatically identifying and analysing hidden correlations in extensive data sets.

#### **3.4.4 System dynamics**

System dynamics is a method capable of enhancing causal thinking as it focuses on causalities and not on singular events. In order to analytically capture the essential

system behaviour and to create a simplified but realistic representation of an examined case in a modelling environment, workshop course learning is recommended.

In order to gain modelling experience and access to the characteristics of different system dynamics tools, the author became member of the German chapter of the global System Dynamics Society ([www.systemdynamics.de](http://www.systemdynamics.de)) and of the Association for cross-linked thinking and complexity management (Gesellschaft für vernetztes Denken und Komplexitätsmanagement e.V.). Based on in-depth experience of society members with the comparable tools “Vensim” (distributed by Ventana Systems, Inc., USA) and “Process Modeler” (distributed by Consideo GmbH, Germany), in the course of a programming workshop, a discussion took place about the intended academic use and the suitability of each programme package.

#### **3.4.5 Evaluation process and decision**

The comparative evaluation of potential modelling and analysis software solutions was based on the following criteria:

- Consideration of the expected amount and quality of survey data.
- Assessment of the specific applicability to the research context.
- Evaluation of the level of flexibility in the application.
- Cost of a single user license.

The decision was taken in favour of system dynamics because it allows the processing of multi-faceted input data and provides quantitative result rankings. The system dynamics modelling software used in the present research is “Process Modeler” (version 7.5.8). The company generously provided a student license, which reduced software license cost from €1,500 to €150.



### **3.5 System dynamics modelling**

#### **3.5.1 Conditioning of interview data for representation in causal diagrams**

To master the amount and inhomogeneity of the acquired data, the information was systematically sorted within a 2- or 3-stage hierarchical ordering process, in the course of which appropriate classification categories emerged. The next step was to integrate and refine the data to set up the structural input for configuring the causal diagrams.

#### **3.5.2 Polarity of relationship and time behaviour**

In a system dynamics model, the correlation between functional elements requires precise specification containing reinforcing or countervailing polarity of relationship (illustrated by + or – algebraic signs). The causal link between variables originates a consequence in the second (dependant) variable when there is a change in the first (independent) variable. The polarity of relationship determines the quality of a cause's effect and is defined, oriented along Holler (2014) and Chaerul et al. (2008), as:

- A positive polarity indicates that as the cause increases the effect also increases, or vice-versa. When the independent variable changes, then the dependent variable changes in the same direction. Both, the independent and the dependent variable distinctively increase or decrease (Richardson, 1997). The most widely accepted definition is formulated by Sterman (2000): “When the independent variable changes with a positive (or negative) sign, then the following values of the dependent variable will be above (or less) than what they would have been.”
- A negative polarity indicates that as the cause increases, the effect decreases, or vice-versa. Richardson (1997) formulates: “When the independent variable changes, then the dependent variable changes in the opposite direction. If the independent variable increases, the dependent variable decreases, or vice-versa”. Sterman (2000) outlines: “When the independent variable changes with a positive (or negative) sign, then the following values of the dependent variable will be less (or above) than what they would have been.”

Different impact time behaviour is considered by defined time delays after which an independent variable starts to create effect on the dependent variable (--- for short-term, -|- for medium-term and -||- for long-term).

### 3.5.3 From a course-setting image towards higher focussed analyses

The system dynamics examination process is carried out gradually starting with a first fundamental and trendsetting model followed by the development of two more detailed and higher focussed models. The consecutive elaboration process is shown in Table 7.

**Table 7: Overview on successively elaborated system dynamics models**

	<b>SD-model 1 ("Basic")</b>	<b>SD-model 2 ("Reinforcing")</b>	<b>SD-model 3 ("Countervailing")</b>
<b>Purpose</b>	Indicative model to direct the research by a "look ahead and reason back" approach	In-depth analysis of second- ranked (grouped) impact factor identified by the basic model	Cross-check of the research by taking a diametrically opposite perspective
<b>Input (# replies)</b>	234	671	1,712
<b>Target factor</b>	Full-commercial power generation by marine energy	Showcase commercial-scale projects / successful demonstrators	Negative impact on the development of marine energy
<b>Group terms</b>	7	3	5
<b>Sub-group terms</b>	-	8	9
<b>Generic terms</b>	39	26	20
<b>Conclusions derived from</b>	Ranking of (grouped) impact factors	Ranking of (combined) top-level driving factors, correlation of representative interview statements and elaboration of prioritised strategy options.	

In the first SD-model, the marine energy development trajectories are determined and the key milestones defined after calculating the ranking of impact factors for achieving full-commercial generation. In the second and third models, top-level driving factors decisive for market-competitive electricity generation are identified. Enriched by corresponding expert interview statements, the findings are substantiated and used to elaborate prioritised strategy options for consideration in stakeholder action plans.

### 3.5.4 Insight matrix

For the assessment of the calculation results, a so-called insight matrix shows how the target is affected by each individual impact factor. The insight matrix is the graphical output format of the system dynamics tool that was used.

The presented insight matrices are interpreted as such: the greater the distance from the origin of the system of coordinates, the more significant an impact factor is. Thus, the consequential representation into numerical values qualitatively reflects both characteristics: the effective sum of an impact and the relevance of its time behaviour.

On the x-axis, the effectual sum of the reinforcing (right-hand) and countervailing (left-hand) impacts on the final target is represented for each individual impact factor. The y-axis reflects the time behaviour characteristics of each impact factor and shows at what level the effect on the final target will change over time, i.e. whether the impact will further increase or further decrease over time.

By choosing different ranges of processing cycles, time-dependent effects can be displayed and identified. In the present research, for the insight matrix analysis, only long-term projections were chosen because stocks and flows have not been used, which reduces the impact of non-linear effects.

### **3.6 Chapter summary**

The following conclusions are drawn from the chapter:

- The finalisation of the technology development and market integration of marine energy requires the management of multi-level techno-organisational challenges under financial constraints. The correlated processes need to be embedded in existing innovation network contexts and can thus be considered as forming complex dynamic systems. The present research method is designed to adequately operate in such environments. In the framework of the corresponding strategic management and organisational development, qualitative feedback modelling has emerged as the appropriate concept.
- The research method allows the analysis of the entire spectrum of volatile risk complexes and the identification of strategic targets and pivotal milestones.
- The approach comprises a combination of transparently processing cross-category expert interview data and the sequenced determination of prioritised strategy options substantiated by corresponding interview statements.
- The research enables a circular interplay between knowledge compression and targeted knowledge diffusion. The presented strategy-finding process is flexible and re-adjustable to new developments and altering priorities.
- Systemic problems can be addressed in a coherent manner by high-level coordination between stakeholders.

- The design of the questionnaire and the selection of the interviewees form key elements of the intellectual contribution and are strong determinants for the quality of the results from the work.
- By concentrating the research on UK and Ireland, the survey population size reduces to 190. When applying standard statistical equations and parameters used for mass surveys with several thousands of interviewees, a minimum sample size of 64 results. As the research is of a phenomenological nature and uses a qualitative approach, different formula apply as shown in more recent papers. By applying the corresponding equation and usual parameters for the confidence level, a minimum required number of 29 interviews is calculated. This value confirms the adequacy of the number of respective interviews (30) performed.

The described method and materials form the basis of the further work. To make full use of the potential by the holistic setup, it is necessary to regularly check if the research activities are consistently directed towards overarching aspects and on the strategic orientation of the sector. It needs to be ensured, that singular tasks and detail questions relevant only for a limited circle of individuals are considered but do not receive undue attention.

## **4 PRIMARY INTERVIEW RESULTS & STATISTICAL FINDINGS**

A comprehensive set of qualitative and quantitative questions was developed for the empirical data collection process (Appendix B.2). With the aim of creating a retrievable set of data for ease of reference, in a first stage, the primary interview statements were put into context and compressed without software support. Certain findings of the subsequent system dynamics-backed analyses can therefore be cross-checked with unfiltered primary results.

This chapter presents brief textual summaries for essential interview questions summarising exemplary and coherent expert statements. Reference is made to Appendix D where the original replies are listed in full length.

### **4.1 Calibrating the research: Target project characteristics**

The intention behind this first set of questions is to help harmonise and uniformly direct the research. Interviewees were asked when they expect marine energy will be considered as a common concept and what the average MW-rating and installation cost of commercial-scale arrays would be.

By this approach, it is ensured that all subsequent findings and analyses concentrate on an identical virtual reference project. Without that gradual calibration, one interviewee might have made associations to prototype test facilities whereas another might have concentrated on far-future multi-array schemes.

It should be recollected that the research focuses on virtual tidal current and wave power projects in Europe with the following characteristics: capacity ~40 MW, implementation ~2025, investment ~120 m€.

### **4.2 Knowledge transfer and learning from neighbouring sectors**

#### **Which are the most valuable experiences gained by early movers?**

Based on marine operation experience made by front running companies, support can be provided to more precisely direct the further development of the technology.

In the first place, it was found essential that real site measurements are made in order to fully understand the resource and to enable realistic energy yield predictions.

Based on offshore deployment and installation experience, a need for iterative design and build processes was communicated.

As marine energy is a risky business, early market entry is seen as critical. Demonstrating the viability of the technology to investors is key to access further funding. At the present stage of development, reliability is considered as more important than efficiency. As national planning systems are partly considered as complicated and time delaying, the importance of early engagement with regulatory authorities was underlined. Experience shows that the time and cost required to develop devices is greater than expected. Incremental advances are considered as expensive and bringing the technology to market is difficult.

### **Which lessons learnt in offshore wind can be transferred to marine energy?**

Lessons learnt from experience in the offshore wind industry suggest the need for improving reliability, which can be summarised by the statement that “availability is king”. Technological parallels between the two sectors mainly concentrate on materials, support structures, design and layout of the machines as well as on offshore electrical infrastructure (e.g. subsea power aggregation, transmission system and grid integration). The challenge of working at sea in hostile conditions is considered as comparable in both sectors. It is vital to have infrastructure in place to support deployment and maintenance. Regarding project structuring and risk management, the importance of integrating dynamic positioning (DP) vessel operation, ocean floor drilling and remote operated vehicle (ROV) techniques was underlined.

Apart from topics around device reliability and technology learning, it is expected that marine energy can profit from experience on implementing offshore wind farms and operating them 24/7. Regarding the required reduction of capital expenditures (CapEx) and operation expenditures (OpEx), it was emphasised that the cost of electricity production depends on the capacity deployed. Knowledge sharing to avoid duplication of time and effort is essential which might also enable synergy effects by coupling different kinds of renewables. Health, safety, security and environment (HSSE) requirements are regarded as similar in both sectors.

Further statements focussed on contracting approaches and on how to efficiently manage the consenting, leasing and licensing process.

### **Which lessons learnt in oil & gas can be transferred to marine energy?**

It must be accepted that offshore intervention is expensive which requires optimising it within constraints. It is expected that marine energy can profit from design and use of materials employed in the offshore oil & gas business. However, as this sector is characterised by expensive bespoke and one-off technology (“big problems, big money”), some interviewees considered that “not too much” can be transferred to marine energy. Even the differences in budgets are repeatedly mentioned, similar problems will have to be solved in marine energy with lower budgets.

Regarding the marine energy technology development, the standardisation of components is seen as essential. The design must focus on installability, reliability, operability and survivability for which redundancy concepts need to be developed.

Parallels between the sectors were found with regard to requirements for geotechnical analyses, foundation design, corrosion protection and bio-fouling control.

Apart from experience in 24-hour subsea marine operations, project management skills are considered as a valid reference regarding manpower and logistics.

Risks shall be shared in a contractually optimised manner. Focus needs to be put on supply chain and HSSE requirements.

### **Knowledge from which other sectors might be useful for commercialisation?**

The replies received reflect the significant technological challenges the sector faces.

Experience of large OEMs (original equipment manufacturer) in the context of conventional or renewable power projects (i.e. on the contractual setup) as well as knowledge from other high technology industries (i.e. on system design) is considered as transferrable. Specific sectors mentioned are nuclear (risk management), maritime industries (port structures, naval fabrication, low cost supply chain), academia (R&D, composites and advanced materials), insurance companies (transport, equipment at site), energy utilities (consenting process, permits, agreements), aerospace and defence (management of high value assets, probabilistic models) and serial production industry (scale-up and mass production).

Projects and industries with pilot character that managed to bring innovative technology to market can provide principal guidance and orientation.

### **4.3 Achievements and planning**

#### **Which were the main achievements of your organisation for the development of marine energy?**

Stakeholders driving policy recalled successfully funding projects, the work on revenue support schemes, the implemented marine actions plans and the establishment of European research alliances.

Experience with full-scale devices in the water and successfully licensed grid-connected tidal turbines was emphasised. Having secured a 20-year power purchase agreement was communicated as a key contributor to advance the sector.

Achievements in the context of technology learning were related towards better understanding of the sources of underwater noise and minimising the environmental impact. An improved understanding of tidal resource characteristics was reported, based on progress in modelling techniques and numerical validation.

Having continuously developed the high-risk marine energy business during the 2007–2008 global economic crisis and the subsequent European debt crisis is seen retrospect as a significant achievement.

#### **Which internal targets appeared more difficult to reach than originally planned?**

Difficulties in funding and financing were identified as the main causes for setbacks in achieving internally-set goals. The development of marine energy would have been much quicker if more money would have been available. Regarding technological aspects, difficulties were created because communicated TRLs (technology readiness levels) were not as expected.

Speeding up commercialisation is limited by the difficulties in bringing in skills from the oil & gas sector and by missing consensus over standardisation. The challenge is to timely “bring some 10 MWs in the water” and to minimise the lack of experience.

#### **The initiatives or activities of which stakeholders are key for the progress?**

The role of the UK Government is considered as essential for the progress achieved, based on which device manufacturers successfully build. With regard to funding, the “5 ROCs/MWh” incentive mechanism represents a positive commitment and supports



the establishment of test sites and the development of marine energy arrays. Attracting investment and the provision of funding are essential for the development of the sector. The involvement of major industrial companies simplifies supply chain support. Collaborative research has brought relevant progress. The integration of policy, science and licensing represents a pragmatic approach and simplifies regulatory issues.

### **Which are main reasons why marine energy has not developed more rapidly?**

The basic reason why the sector has not develop more rapidly is related to the direct correlation between the difficulties in funding and the ongoing technology maturation. The development of the technology is more expensive than expected and the necessary funding to cover project costs is far greater than initially anticipated (“funding drove the engineering”). In the earlier formative years, an initial naïvety and over-optimistic developers prevailed. With increasing cost and limited resource for acquiring necessary investment, developers were forced to move at a slower pace. The reported difficulties in getting private investment correlate to the global economic situation at the time of the interviews.

The uncertainty about the monetary payback of projects is related to limited knowledge about the expectable service life of devices. In response to the question, the interviewees replied that there was not enough focus in proving the technology and to reduce the uncertainty in system performance.

It was reported that the industry presented itself as being at a more advanced stage of development than it really was. This led external stakeholders (e.g. policy-makers and funding bodies) to direct their resources towards tackling barriers other than the one the industry immediately faced. Early life faults need to be engineered out of commercial products prior to deployment. Intensive sea trials are seen as essential to support the further development process.

Some interviewed experts criticised that there is too much focus on incremental technology development and that the diversity of available systems is too high (“too many different concepts under development”). A lack of collaboration in the industry was mentioned and partly explained by the early commercial pressure in the sector.

### **In which areas is research most required to accelerate marine energy?**

The vast majority of replies relate to further required technology learning. Based on system-level engineering and optimisation, an improvement of the reliability of components and devices is expected. By a “whole system evaluation” process, an improvement of the integrity of devices is expected. A clear recognition is that applying systems engineering principles is seen as crucial. Focussing on common concepts (to enable “cheap ways to harvest marine energy”) and not on specific technologies was recommended.

Regarding electrical installations, apart from improving component efficiency, need for research was identified on the power take-off installations, seabed mounted cable systems and grid interface equipment. On the mechanical side, deficits in knowledge were identified on structural support systems to install the energy converters in challenging locations. Turbulence and extreme loadings require larger-scale model testing (of arrays with multiple devices). With regard to marine operations, cost-effective installation and retrieval methods are expected to minimise O&M efforts.

Concerning cooperation with universities, it must be kept in mind that industry programmes usually have shorter timeframes than academia. To simplify the interaction, coordinated project phasing and regular bilateral coordination is necessary.

Further studies on environmental impact and marine life interaction are necessary.

Design and financial modelling tools help to facilitate cost-effective array-scale developments, which are required to prove the feasibility of marine energy. Apart from the need to look out for cost-saving potential, it is necessary to systematically identify how to attract funding. Strategic development roadmaps need to consider potential benefits by interlinking different forms of renewable generation initiatives or projects.

## **4.4 Cost aspects**

### **Where are the greatest concerns for delays and cost-overruns in projects?**

For some project cases, an initial underestimation of the marine conditions (e.g. weather, waves, turbulence) was reported. Working offshore is generally difficult and expensive as work windows are restricted. The availability of heavy marine services and DP vessels is limited due to the competition with the oil & gas industry supply chain. The vessel spot market prices can fluctuate significantly, resulting in cost overruns if required for longer than initially thought.

With regard to marine energy technology performance and technology readiness, an underestimation of risks and uncertainties was indicated. Key difficulties are correlated to device reliability and durability as well as on formally and technically managing the grid integration. A number of interviewees referred to legal permitting delays caused by the regulatory process.

Regarding financial aspects, it was reported that manufacturing, transport and installation cost were generally underestimated. As reliability and performance are key indicators of the quality of devices, publically known failures made it difficult to secure uninterrupted investment.

### **Where do you see potential to get the cost for utility-scale projects down?**

Interviewees saw cost reduction potential in various categories.

In order to prevent the same mistakes being made time and again, shared learning by project developers is recommended. Closer collaboration between technology developers (OEMs) and project developers was indicated. Bringing in offshore oil & gas marine operations and defence industry experience and expertise will help to avoid common mistakes being repeated. It is expected that in the course of the technology convergence process and the further industrialisation of the sector, productivity will be improved and thus significant economies of scale achieved.

Regarding technological aspects, cost reduction potential is seen in grid connection sharing between multiple (marine energy and other renewable power) projects. In the course of array-level project design, low-cost strategies for the interconnection of devices can be implemented.

Computer modelling is one element in developing more efficient deployment and retrieval methods as well as optimised O&M strategies. Due to the detected over-engineering in oil & gas norms, the need for new international standards, e.g. by the International Electrotechnical Commission (IEC), was emphasised. Respondents confirmed that pilot zones are necessary for equipment endurance testing.

The importance of focussing on LCOE and not on CapEx was mentioned. Nevertheless, optimum LCOE often involves increased CapEx by the use of high quality components (extended service life) and a certain degree of over-engineering (to enhance reliability). Improvement potential is seen by installing collaborative contracting<sup>20</sup> or collaborative procurement<sup>21</sup> and forcing contract standardisation.

### **What are the main factors driving up the insurance cost?**

Interviewees reflected that the technology is challenging, there are many unknowns and major industry success stories are missing. The marine energy sector is considered to a certain level as experimental with high levels of risk, leading to a very limited insurance market and high insurance cost. The insurance companies take into account the risks by the challenging offshore environment and assess experienced difficulties or reported device failures. At the time of the interviews there were no major reference projects and some unfortunate experience in offshore wind, which led insurance companies to estimate “safe” margins.

Further critical arguments related to the inadequate demonstration of risk management in the sector and the lack of proven long-term operation. The limited standardisation of devices is seen as critical (“no standards – no results”).

The high cost of offshore failures increases the price of insuring risks.

Considering the financial environment (at the time of the interviews) and the history of claims in past projects, achieving commercial return is seen as very difficult.

---

<sup>20</sup> A collaborative contract is an agreement that describes the framework, responsibilities and contributions for participants working together on a defined activity or project. Collaborative contracts allow purchasing goods, services and works collectively in order to achieve favourable conditions.

<sup>21</sup> Two or more organisations that agree to work together having identified the benefits that can be achieved by aligning their purchasing power and resources to deliver financial savings, efficiencies and effectiveness without any detriment to the project(s) and/or service objectives.

## **What measures can be taken to avoid cost increase as in offshore wind?**

Below questions a) to c) were formulated based on the findings reported by the UK Energy Research Centre (2012) on cost increase in offshore wind in the UK from 2005 to 2009.

### **a) Measures to reduce the “complexity of the planning process”**

The complexity of the planning process was generally identified as causing slower than expected progress, but it is not a significant contributor to cost escalation. One interviewee even explained that the planning process is not complex and another outlined that it is recommend to wait until complexities have been sorted out in offshore wind.

It is recommended to adhere to best practice and experience by developers and to work on industry-wide planning protocols and standardised design approaches.

Having a single regulatory body and the provision of guidance on how to get consent helps to reduce cost (e.g. in the UK there are two: one for England and Wales, called Marine Management Organisation and Marine Scotland). A better sharing of engineering and environmental data is recommended as improved project planning will facilitate consenting. The interviewees acknowledged that licensing has been greatly simplified in the last few years.

### **b) Measures to reduce “supply chain bottlenecks”**

A number of interviewees stated that from their business perspective there were no supply chain bottlenecks at the time of the interviews.

Some comments received were directed towards ensuring that the port infrastructure is established and to aim to employ smaller and simpler vessels.

Through accurate roll-out forecasting and good cooperation between developers and the supply chain network, potential bottlenecks are expected to be avoided (“realism in schedules and early notification to suppliers”).

Transfer of technologies from offshore wind and the creation of a cluster of suppliers (cooperation between developers for similar equipment) are suggested as appropriate measures.

### **c) Measures to increase the “equipment reliability”**

Communicated strategies to improve the reliability of the tidal and wave energy converters and correlated ancillary systems mainly start with strengthening design guidelines and improving testing procedures as well as fostering knowledge sharing. Apart from consequently focussing on reliability in the system design concept, the importance of designing for installation and maintenance purposes was emphasised. Applying engineering concepts from offshore wind, that support the development of standard design solutions is seen as key.

The need for designing out complexity and failure points as well as applying concepts of modularity and redundancy was emphasised. It was stated that the techno-economic optimisation requires trading-off cost and reliability.

More testing under open sea conditions and improved equipment performance monitoring have high priority. This might be supported by bringing in major industrial expertise and setting up supplier competition. A coordinated approach to collect data on failures, i.e. FMEA (Failure Mode and Effects Analysis) and reliability modelling is recommended. A structured certification process is required.

Emphasis is put on capturing knowledge from other sectors and on lessons learned by ongoing project implementations.

## **4.5 Risks**

### **4.5.1 Which are the key risks in commercial-scale marine energy per project phase?**

The interviewees were invited to think about risks that are characteristic for each main project phase:

- Although the project initiation and concept phase might normally not be viewed as a high-risk phase, in fact it is. Decisions made during this initial phase can have a larger impact on the project outcome than ones made later in the implementation process. Identifying suitable locations and selecting the most appropriate site is a responsible task that needs to be performed based on only limited data availability.

Experience shows that in the course of raising capital, it is necessary to avoid over-optimism, especially with regard to LCOE. There are currently no reported “excellent” examples that can be made reference to. A trade organisation’s marine energy specialist underlined the basic importance of the resource assessment and its effect on LCOE data.

- Consenting risks occur in the planning and design phase and can be significant. Due to limited experience with executed projects and the lack of proven design tools, selecting the right technological concept is a challenge. Change of design (due to late information or data inaccuracies) is costly after having submitted the licensing documents.

Apart from the lack of resources and the pervasive time pressure, many project initiatives suffer from a lack of a systematic approach to risk management. There is insufficient project structuring knowledge on how to arrive at a bankable proposition.

- The manufacturing and testing phase is where serious costs start to be incurred and if things go wrong, the financial implications can be significant. In the past, high costs were caused by gaps in the supply chain and the unsatisfactory quality of outsourced components.

Testing customised equipment and systems is costly and needs to be based on established documents. Necessary third party certification is difficult to organise because of missing standards and different quality control approaches.

- During the erection and commissioning phase, cost overruns due to offshore conditions (accessibility, vessel availability, weather window) represent a key risk. In the past, delays were caused by inefficient commissioning activities and longer than needed downtimes.

Due to a lack of planning experience, cost increases can occur. It needs to be ensured that the marine operations challenges are fully understood. Getting insurance for this project phase is difficult.

- Concerning the risks in the commercial operation phase, there is no significant experience to build on. The technology was considered as unproven and so likely to have high failure rates leading to increased O&M cost and reduced energy yield data. A high failure rate could have a significant impact on the project economics.

Unclear response times for vessel operation activities to perform repair works in case of unplanned outages require attention.

A potential reduction in fiscal incentives and changes in the support mechanisms by government might threaten the financial performance of a project. Having a guaranteed market that buys electricity at agreed rates widely eliminates that risk.

- The decommissioning phase represents a low risk because it involves conventional techniques. Nevertheless, there might be the risk of an inability to decommission due to bio-fouling and corrosion. Some developers identified an underestimation of the effort needed and named a consequential cost increase.

A different standpoint is to look for renewal or repowering rather than decommissioning. There should be a consent clause regarding what can and cannot be left in-situ. Changing environmental legislation might create an impact.

#### **4.5.2 Risk transfer and risk propagation processes**

The research intention behind this investigation was difficult to explain to the interviewees. The participants were asked to think about project situations in which risk transfer takes place or when effects through risk propagation start to create impact.

Due to the novelty and overall character of this part of the examination, only a few substantial statements were received after briefly explaining the context based on the exemplary cases outlined in the following.

In the course of a complete tidal array project life cycle, the quality and contractual responsibility for the generation capacity (“energy yield”), experiences several step changes.



The responsibility for the energy yield data is transferred repeatedly:

- Project initiation and concept phase

A research institution or consultancy firm initially calculates the energy yield by numerical modelling based on literature and available field data. At the example of an investigated 600 MW tidal array project, the total uncertainty of the calculated energy yield was determined at +35% to -30% (Bucher, 2014).

- Planning and design phase

For a project developer, the estimated energy yield data form the basis for further planning and development of the project. The important decision for the type of technology is taken and detailed tender documents are prepared.

- Manufacturing and testing phase

The selected manufacturing firms dimension their components (turbine, generator, power take-off and auxiliary systems) according to the data in the signed contract. Their responsibility for the efficiency is limited to a fixed percentage-value. The precision of turbine and generator performance guarantee data is – in conventional hydro – within a tenth of a percent.

- Erection and commissioning phase

The contracted firms install the equipment at site under their responsibility. During the final testing and commissioning, minor adjustments can be made and control parameters optimised. Due to the widely fixed machinery layout, the improvement potential with regard to increasing the energy yield is minor at this time. The take-over certificate is issued based on compliance with the contractual obligations. In the case where contractual values are not reached, significant compensation payments can apply, depending on the agreed contractual terms and conditions.

- Commercial operation

The owner bears the long-term risk for the annually achieved energy yield. Depending on the terms of the agreement with the investor, the owner might suffer financial damages in cases where the calculated yield is not achieved.

A representative from an engineering consultancy outlined his perspective regarding the above risk transfer processes as follows: “In offshore wind, it is common for risk to be pushed down the supply chain so that contractors end up taking on the majority of project risk. This is probably a suboptimal allocation of risk and economics could be improved if risk were allocated differently, so that those best placed to manage a given risk also take own that risk.”

One interviewee predicted that risk ownership in marine energy will be the same as in offshore wind, where the optimum is still to be worked out.

A project developer’s representative outlined that risk transfer processes are highly site- and project-dependant and that conflicts of interests have to be taken into account.

A device manufacturer’s representative underlined the difference between “internal performance” (i.e. in the laboratory or test fields) and “grid operation performance”.

With a focus on risk sharing, in a further statement it was outlined that “installation companies should pick up risk from device manufacturers”. It shall be noted that this might be critical as offshore installation firms have only a limited scope of services and minor budgets compared to the device manufacturers. Furthermore, they usually do not have insight into the core technology and thus cannot take such responsibility.

As marine energy represents a novel business, aspects of insurability need to be taken into account. To achieve insurance coverage as in more mature businesses, clear limits of work and responsibility need to be fixed.

It can be summarised that the project phases in which risks and responsibilities are transferred are decisive for the project success. In line with a statement above, the optimum form of risk distribution will likely emerge by itself in the long-term.

After passing the pilot and pre-commercial phase, marine energy projects will be implemented under similar contractual frameworks as other renewable projects.

### 4.5.3 Correlation of risk types to estimated risk levels

For the 33 risk types pre-defined by the questionnaire in Appendix B.2 and listed in Table 8, a total of 1,495 interview-based risk level estimations in categories of low, mid and high were received.

**Table 8: Statistical ranking of risks**

Risk category / Risk type	Risk description	Risk level		
		low	mid	high
Strategic	Regulatory issues		x	
	Obtaining license to construct		x	
	Obtaining permit for grid connection		x	
	Environmental impact		x	
	Shoreline evolution/sediments	x		
	Public perception		x	
	Accidents		x	
	Conflicts of use			x
	Professional fishery			
	Offshore wind	x		
	Military	x		
	Leisure activities	x		
	Infrastructure and logistics		x	
	Capability of shipyards/ports/vessels		x	
	Access to skilled workforce		x	
	Supply chain constraints		x	
Financial	Project management			x
	Keeping time schedule			
	Keeping budget			x
	Funding requirement			x
	Profitability requirement		x	
	Appropriateness of feed-in tariff			
	Achievement of energy yield data		x	
	Insurance requirement			x
	Acceptable insurance cost			
Technological	Ambient requirements		x	
	Ground conditions			
	Extreme weather situations			x
	Energy conversion system		x	
	Manufacturability			x
	Installability			
	Mooring		x	
	Power export		x	
	Inner-park cabling			x
	Regional grid capability			
	Operational risks			x
	Reliability			
	Operability		x	
	Survivability			x
	Maintainability			x
	Training of staff	x		
	Health and safety		x	

Based on the statistical evaluation, each individual risk type was allocated to one of the 9 risk levels (very low to very high) detailing the 3 main categories.

The following can be concluded:

- The two top-ranked risks were identified as “reliability” as a technological risk and “achieving funding” as a financial risk. Apart from installing, maintaining and connecting the energy conversion systems, ensuring their long-term survivability was classified as a high risk. Regarding the management of marine energy projects, keeping time schedules and working within budget were seen as highly challenging (e.g. by extreme weather situations). Achieving insurance at acceptable cost was seen as critical. As the only significant risk regarding conflicts of use, professional fishery was mentioned.
- On the medium risk scale, regulatory aspects such as obtaining a sea use license or a permit for construction and grid connection are found. In the group of soft risks (categorised by less statistical data and the difficulty to determine action), the potential impact on the marine flora and fauna, the expected public perception and aspects of health and safety were mentioned. Further medium risks relate to infrastructure and logistics (capability of shipyards/ports/vessels, access to skilled workforce and supply chain constraints). Profitability directly relates to the projected energy yield data and the appropriateness of the feed-in tariffs.
- Shoreline evolution and conflict of use referring to offshore wind, military and leisure activities are seen as low risks.

## **4.6 Chapter summary**

The chapter finalises the introductory and preparatory stages of the work.

The thesis target is put into the wider context and the research questions are formulated. The literature references are critically reviewed and the method and materials comprehensively described. The primary interview results are summarised.

With the next chapter, the core research activity begins by setting up a first qualitative system dynamics model building on the data and knowledge elaborated up to here.

## **5 IDENTIFICATION OF PIVOTAL MILESTONES**

The previous chapters served to explain the research context, to describe the interview-based system dynamics modelling approach and to present excerpts from the raw data gained in the course of the expert interview series.

This chapter begins the fundamental analytical part of the thesis, in which the first of three system dynamics models is developed and tested. The aim of the analysis is to rank the impact factors and to identify the key milestones for successfully commercialising marine energy.

### **5.1 Necessity for SD-model 1**

Electricity generation by tidal current and wave power arrays represents a radical innovation that is confronted by major technological and financial challenges. Even significant development took place in the recent years driven by offshore test facilities and subsidised pilot projects, an increasing time pressure to reach market acceptance is recognised because such artificially created learning spaces are typically maintained only for a limited time. The presently available so-called incubation rooms were created with the goal of developing the technology to the level of reliability required to compete in the energy market.

With the near-future prospect of realising profits in a new power market segment, there should be a strong motivation for cooperative interaction aimed at jointly achieving market acceptance. Regarding the challenges the marine energy sector faces, the presented approach based on openness and transparency is seen as more credible and appropriate than conventional company-internal and thus closed-circle strategy determination. The presented results were achieved by rethinking of how to reliably govern a politically relevant technology maturation processes.

The primary literature lacks a coordinated approach to efficiently reach commercial operation of marine energy arrays. To appropriately orient the sectorial development trajectories, the identification of essential impact factors and the determination of pivotal milestones is required. As such, the mitigation of decisive risk complexes hindering the market breakthrough can be targeted and allocated in time.

The idea for the initial SD-model emerged by thinking about a principal strategic rule known in the theory of games as “look ahead and reason back”. According to this concept, “the player anticipates where his decisions shall ultimately lead to and uses this information to calculate his current best choice” (Dixit and Nalebuff, 1991). In Bucher (2013), this “look ahead” was not defined by anticipating where a player’s “decisions shall ultimately lead to” but by focussing on the reason for the existence of any large-scale power scheme: To guarantee market-competitive electricity generation – and in the present case based on marine energy technologies.

The intention behind this first modelling task is to gain a comprehensive understanding of the characteristics of ongoing and planned marine energy activities. To provide the basic data input, the interviewees were motivated to think about qualitative impact factors (e.g. the global policy framework, environment directives and energy security) that are considered as essential for achieving commercially viable generation. The quantitative results provided by the software tool are substantiated by qualitative interview statements, either with supporting or hindering effect on the development of the marine energy sector.

## **5.2 Full-commercial power generation by marine energy**

### **5.2.1 Definition of target factor**

As the examination is carried out gradually starting with a fundamental and trendsetting model, the first target factor was defined with a focus on identifying the strategic marine energy development trajectories and key milestones for achieving market-competitive electricity generation.

The target factor was formulated in qualitative manner as “full-commercial power generation by marine energy”.

### **5.2.2 Reference to questionnaire**

The model is based on the replies to the following topic in Appendix B.2:

**# 5 Main impact factors on reaching the target “full-commercial marine energy”.**

### **5.2.3 Group terms / generic terms**

Out of 234 qualitative replies defining the impact on achieving full-commercial power generation, 118 were supportive and 116 hindering for the development of the sector.

In a first step, each reply was analysed regarding the principal thematic implication. In an upstream evaluation and sorting process, 7 high-level ordering terms (“group terms”) were defined. No sub-group terms were defined.

In a subsequent step, replies with similar alignment and related content were grouped. As a result, 16 positive and 23 negative generic terms were defined.

According to the number of nominations of each constituting reply, the generic terms were allocated to the 7 positively formulated group terms.

Consequently, each interview reply is allocated via one of the 39 generic terms to one or more of the group terms as shown in Table 9. For example, the generic term “strong and long-term commitment from government” feeds via the 4 group terms “consolidated business development”, “efficient consenting, leasing, licensing”, “appropriate project financing” and “reduction of CapEx and OpEx” onto the final target factor.

#### **5.2.4 Model configuration**

The basic model structure is defined by the number of generic terms and their intermeshed correlation via the group terms to the final target factor. In the causal diagram in Fig. 5, the generic and group terms are visually arranged in a manner to reduce the number of arrow crossings and thus to ensure improve the readability. Each generic term connects via one or more group terms towards the target factor located on the right-hand bottom side.

The generic terms act according to their percentage-wise distribution<sup>22</sup> onto the group term “consecutive technology learning”. The effect of the group terms on the final target factor depends on the distribution of impact levels. In the present example, “consecutive technology learning” with 26 processed replies leads to an impact of 11% as shown in Fig. 5 and Appendix E.1.2.2.

Before graphically setting up the causal diagram, all structural sorting, configuration issues and numerical distribution calculations were finally addressed and resolved in a spreadsheet.

---

<sup>22</sup> As the used software calculates internally according to proportions, it is not necessary that the sum of the impact is exactly 100 (in this case 95).

For this first system dynamics model, the hierarchical ordering process is outlined in detail. It comprised the following steps:

(i) Target factor (“Full-commercial power generation by marine energy”)

(ii) High level ordering (“group terms”)

All 234 received replies were analysed and an adequate number of 7 positively formulated group terms to sort the data were defined:

- Appropriate project financing
- Confidence-building device operation experience
- Consecutive technology learning
- Consolidated business development
- Efficient consenting, leasing, licensing
- Encouraging marine operations experience
- Reduction of CapEx<sup>23</sup> and OpEx<sup>24</sup>

(iii) Medium level ordering (“sub-group terms”)

In the example, no sub-group terms were used.

(iv) Low level ordering (“generic terms”)

Out of all interview replies, a number of 24 (8 positive and 16 negative) referenced to “Consecutive technology learning”. For these replies, the following 8 generic terms (5 positive and 3 negative) were defined:

Positive effect on the target factor

- Development of international standards
- Engagement industry / academia
- Focussed support of technology / pilot development
- Satisfactory technology reliability record
- Showcase commercial-scale projects / successful demonstrators

Negative effect on the target factor

- Engineering challenge / technology barriers
- Failed demonstrations / technology failures
- Low ability of developers to work together

---

<sup>23</sup> Capital expenditures: pre-development costs, construction costs, electrical system infrastructure costs.

<sup>24</sup> Operational expenditures: operating and maintenance costs, insurance costs, de-commissioning costs, seabed lease, transmission grid charges.



**Table 9: SD-model 1: Group terms, negative and positive generic terms**

<b>Negative generic terms</b> (hindering / delaying / countervailing)	<b>Positive generic terms</b> (supporting / accelerating / reinforcing)
<b>Group term: (Encouraging) marine operations experience</b>	
Critical events regarding H&S (neg. press)	Attractive marine resource available
Engineering challenge / technology barriers	Showcase com.-scale projects / (...) demonstrators
Environmental pressure	
Grid constraints	
High cost of devices / deployment	
Lack of investor confidence	
No adequate port infrastructure or manuf. sites	
<b>Group term: (Consolidated) business development</b>	
Consolidated business development	Climate change / price of carbon / decarbonisation
Failed demonstrations / technology failures	Clustering (device developers & test sites)
Fluctuating or unclear political support	Collaboration & consolidation between comp.
Fragmented initiatives by unexperienced parties	Engagement industry / academia
Long times to commit to marine energy	Industry growth / trajectory
Low ability of developers to work together	Strong and long-term commitment from gov.
Other renewables	
Subsidy- instead of market-driven developments	
<b>Group term: (Efficient) consenting, leasing, licensing</b>	
Confused regulatory process / policy	Climate change / price of carbon / decarbonisation
Fluctuating or unclear political support	Regulatory framework / regulatory support
Grid constraints	Strong and long-term commitment from gov.
Regulatory req. for project development	
Conflicts of interest (fishermen, shipping)	
Environmental pressure	
<b>Group term: (Confidence-building) device operation experience</b>	
Failed demonstrations/technology failures	Proven O&M models
	Satisfactory technology reliability record
	Showcase com.-scale projects / (...) demonstrators
<b>Group term: (Appropriate) project financing</b>	
High cost of devices / deployment	Climate change / price of carbon / decarbonisation
Lack of investment in supply chain	Feed-in tariff schemes
Lack of investor confidence	Strong and long-term commitment from gov.
Limited access to capital / fragmented funding	Utility and OEM buy-in
Negative global economic situation	
<b>Group term: Reduction of CapEx and OpEx</b>	
Early commercial pressure	Cost-effective way to harvest marine energy
Hidden subsidies in other renewables	Strong and long-term commitment from gov.
High cost of devices / deployment	
Long delays of projects coming on line	
<b>Group term: (Consecutive) technology learning</b>	
Engineering challenge / technology barriers	Development of international standards
Failed demonstrations / technology failures	Engagement industry / academia
Low ability of developers to work together	Focussed support of technology / pilot development
	Satisfactory technology reliability record
	Showcase com.-scale projects / (...) demonstrators

### 5.2.5 Polarity of relationship and time behaviour

For each group term, a positive formulation was used (“encouraging”, “consolidated”, “efficient”, “confidence-building”, “appropriate”, “reduction of cost” and “consecutive”) to simplify the cognitive modelling process. Dependant on the generic terms, with either positive or negative effect on the group terms, the polarities of the relationships were allocated.

The polarity of relationship between all group terms and the target factor is uniformly positive. A number of exemplary relationships are described in Table 10.

The time behaviour is considered as (i) “short-term” for periods before 2020 (symbol ---); (ii) “medium-term” for 2020 to 2025 (-|-); and (iii) “long-term” after 2025 (-||-).

### 5.2.6 Causal diagram

The causes of events (generated by “independent variables” or herein referred to as “generic terms”) and the consequences (“dependent variables” or herein referred to as “sub-group terms”, “group terms” and finally the “target factor”) are represented.

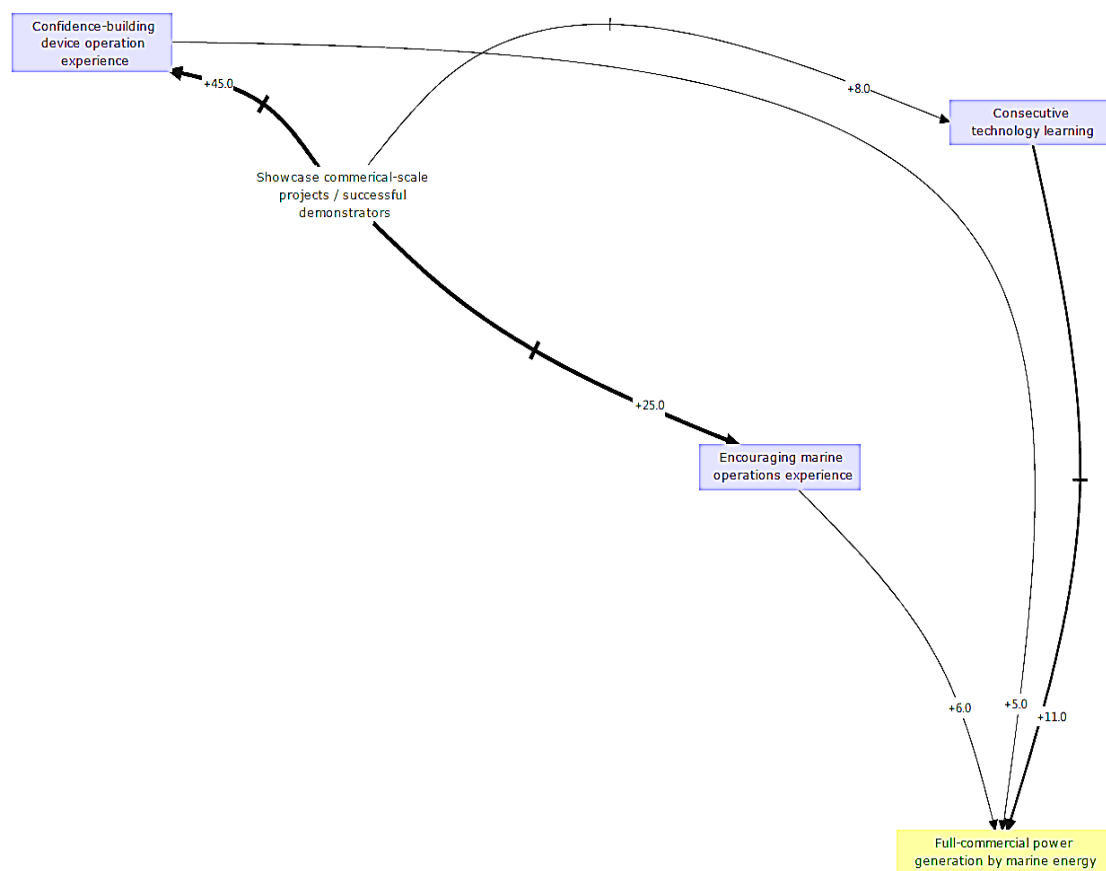


Fig. 4. Exemplary cause and effect relationships (excerpt from SD-model 1)

Fig. 4 shows a representative extract of the SD-model 1 causal diagram. The complete diagram is shown in Fig. 5 and Appendix E.1.1. The high significance of the generic term “showcase commercial-scale projects / successful demonstrators” can be explained by the strong correlation to the target factor “full-commercial power generation by marine energy” via the three group terms “confidence-building device operation experience”, “encouraging marine operations experience” and “consecutive technology learning”.

The relationship between an individual cause and the corresponding effect(s) is defined in its strength by percentage values between 1 and 99. One stands for a weak or low-priority correlation and the maximum value of 99 for a very strong and practically direct dependency. In the present research, values between 2 and 59 appear in the diagrams, as most of the correlations are based on multiple interlinking and therefore split-level effects. The shown percentage values are based on the statistical distribution of the number of interview replies in a specifically examined correlation.

The details of the type and function of the uniform effect correlations between the functional elements are outlined in Table 10. Textual examples are given to describe the apparent reinforcing polarity of relationship.

As an exemplary case, the correlation between successful demonstrators and the level of confidence in the sector is explained in detail. As this correlation is uniform, an increase in the cause (successful demonstrator) creates an increase in the effect (confidence in the sector), and vice-versa. For the “+ +” polarity case, this means that if technology demonstrators work reliably, the confidence in device operation and thus the sector increases. In the contrary case (“– –”), i.e. when experiencing trouble in demonstrators, confidence in the sector decreases for example via negative press, with further correlated negative impacts.

**Table 10: Characteristics of uniform cause and effect relationships**

The basic polarity between cause and effect of the following exemplary relationships is uniform.  
 When the independent variable changes, then the dependent variable changes in the same direction:  
 “+ +” represents a correlation of the type “if the cause increases, also the effect increases”  
 “– –” represents a correlation of the type “if the cause decreases, also the effect decreases”

Cause	Effect	Polarity	Exemplary evidence case
Showcase commercial-scale projects / successful demonstrators	Confidence-building device operation experience	++	Reliably operating devices offers strong evidence and creates confidence in the technology.
		--	Demonstration failures create negative press, raise doubts and increase mistrust.
	Consecutive technology learning	++	The lessons learnt from operating arrays are essential for the development of the sector and for achieving technology convergence.
		--	Without demonstrators, learning would be limited.
	Encouraging marine operations experience	++	Proof of continuous operation and converter survivability is essential in offshore environments.
		--	As the requirements on the technology are high, offshore experience is key. Without reference projects, confidence in the sector will remain low.
Confidence-building device operation experience	Full-commercial power generation by marine energy	++	Investor confidence is key for getting access to capital. It brings the sector in the position to deploy on large-scale and to become market competitive.
		--	Without long-term reliably operating devices, the market breakthrough might not be achieved.
Consecutive technology learning		++	Marine energy is technically challenging and extreme engineering is required in central parts.
		--	Without further R&D and knowledge accumulation, the necessary system maturity and competitiveness might not be reached.
Encouraging marine operations experience		++	Both top-ranked risks (“reliability” as an operational risk and “achieving funding” as a financial risk) become mitigated by experience.
		--	Without positive feedback from pilot installations, investors will prefer other sectors.

To complete the range of possible relationship types, in Table 11, examples for correlations with non-uniform polarities are provided. It is investigated how political support influences business development and regulatory processes. Homogenously defined ordering terms (e.g. group terms of either positive or negative formulation) simplify the cognitive process of configuring the causal diagrams.

**Table 11: Characteristics of non-uniform cause and effect relationships**

The basic polarity between cause and effect of the following exemplary relationships is non-uniform. When the independent variable changes, then the dependent variable changes in the opposite direction:  
 “+ –” represents a correlation of the type “if the cause increases, the effect decreases”  
 “– +” represents a correlation of the type “if the cause decreases, the effect increases”

Cause	Effect	Polarity	Exemplary evidence case
Fluctuating or unclear political support	Consolidated business development	+ –	Rising uncertainty about political support curbs the development of the sector.
		– +	Stable and clear political support creates a positive effect on the development of the business.
	Efficient consenting, leasing, licensing	+ –	Increasing uncertainty about the policy direction complicates and delays the consenting, leasing and licensing processes.
		– +	Reducing the fluctuation in political support correlates with improved regulatory handling.

As an example, the correlation between unclear political support and consenting, leasing, licensing is explained in detail. As this correlation is non-uniform, an increase in the cause (unclear political support) creates a decrease in the effect (efficient consenting, leasing, licensing), and vice-versa. For the “+ –” polarity case, this means that if political support gets more and more unclear, consenting, leasing, licensing become less efficient. In the contrary case (“– +”), i.e. when political support becomes less unclear, i.e. more stable and better known, consenting, leasing, licensing become more efficient.

System dynamics modelling allows insight into the relationship between the chosen model structure and the system behaviour. When changing the model structure or parameters, one can observe the resulting change in the simulated behaviour, which helps understand the risk or problem context. The findings of Lyneis (1999) underline that causal loop diagramming is extremely valuable for eliciting new ideas in teams of thinking about the cause-effect structure of a problem and later for explaining the results achieved by the calculation.

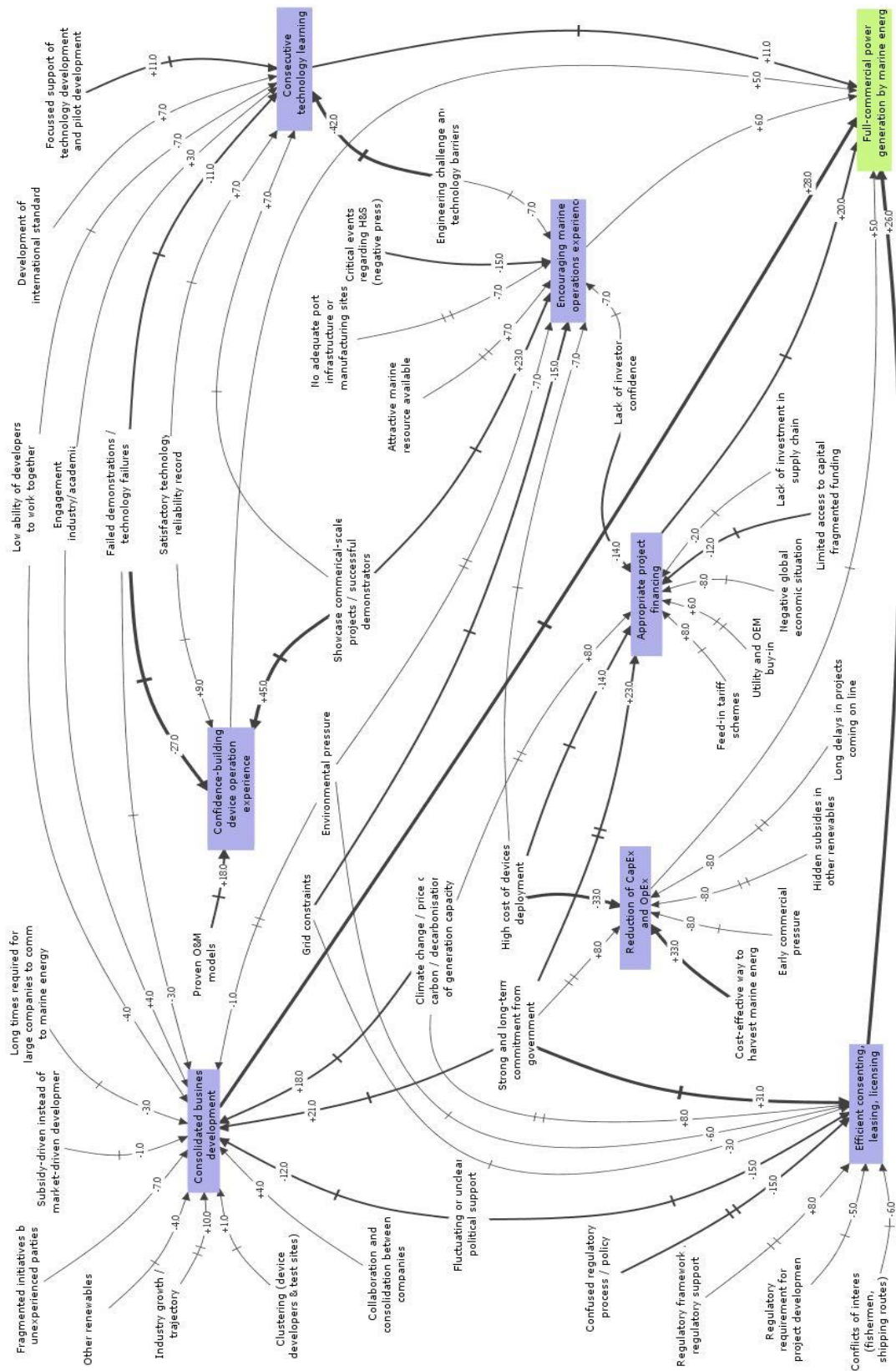


Fig. 5: SD-model 1: Full-commercial power generation by marine energy

## 5.2.7 Insight matrix and ranking of impact factors

Based on the causal diagram, the software tool calculates the effective strength of each impact factor on the final target. It provides as output information the graphical representation of the values in the format of the insight matrix (explained in more detail in paragraph 3.5.4). Dependent on the distance of a displayed impact factor from the axes of coordinates, its significance is determined and given as a percentage-value relative to the strongest determined impact factor. The impact strength of each factor is measured by means of concentric circles correlating the x/y coordinate position with the respective numerical value to be read from the x-axis.

In the right-hand side in Fig. 6, impact factors with positive (reinforcing) effect on reaching the target of full-commercial power generation are shown and on the left-hand side the ones with negative (countervailing) effect are located. If an impact factor is positioned in the right-hand upper half of the matrix, it indicates an increasingly reinforcing influence over time on the final target (defined in the tool as “increasing escalated”). A positioning in the left-hand lower half indicates an increasingly countervailing influence over time (defined in the tool as “decreasing escalated”). The applied item numbering is explained in Table 12 (see “#”).

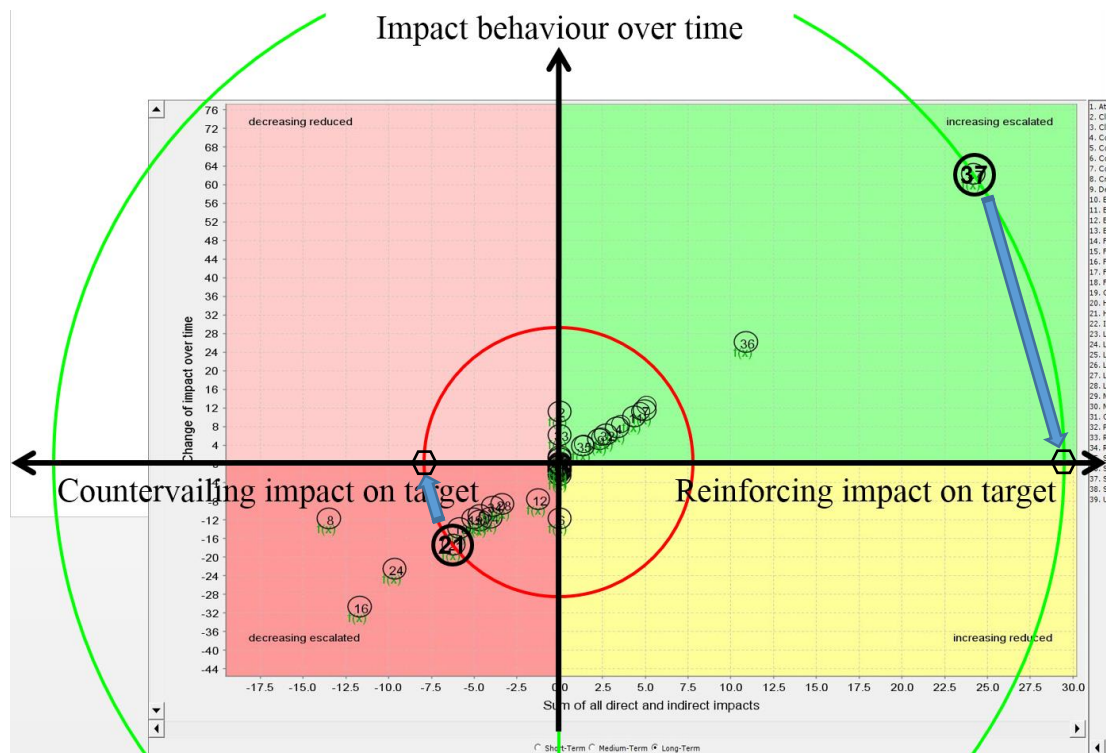


Fig. 6: SD-model 1: Insight matrix (detailed analysis in Appendix E.1.3)

In Appendix E.1.3, the full details of the analysis of the insight matrix for the first SD-model are given. In order to calibrate the analysis by allocating a ranking value of 100 to the strongest impact factor #37 (“strong and long-term commitment from government”), a large green circle is shown. The calibration of the second figure, counting with higher resolution for lower value impact factor readings, is realised via the countervailing impact factor #21 (“high cost of devices / deployment”) with an impact strength of 26 (red circle) that can be identified in both figures.

Table 12 ranks the reinforcing and countervailing impact factors as per the result of the insight matrix measurements outlined in Appendix E.1.3.

**Table 12: SD-model 1: Ranking of impact factors**

Countervailing	Ranking	Reinforcing	Ranking
Fluctuating or unclear political support (#16)	49	Strong and long-term commitment from government (#37)	100
Critical events regarding H&S (negative press) (#8)	48	Showcase commercial-scale projects / successful demonstrators (#36)	45
Lack of investor confidence (#24)	39	Cost-effective way to harvest marine energy (#7)	20
High cost of devices / deployment (#21)	26	Engagement industry / academia (#11)	17
Fragmented initiatives by unexperienced parties (#18)	23	Collaboration and consolidation between companies (#4)	13
Grid constraints (#19)	20	Proven O&M models (#32)	11
Environmental pressure (#13)	19	Climate change / price of carbon / decarbonisation (#2)	10
Conflicts of interest (#5)	18	Development of internat. standards (#9)	9
Failed demonstrations / technology failures (#14)	17	Satisfactory technology reliability record (#35)	6
Regulatory requirement for project development (#34)	15	Regulatory framework / regulatory support (#33)	5
Low ability of developers to work together (#28)	14	-	-
Confused regulatory process / policy (#6)	10	-	-
Engineering challenge / technology barriers (#12)	8	-	-

Some of the factors negatively influencing the achievement of market-competitive generation represent the diametric opposite to positively acting factors. In the further evaluation, they are not verbally repeated but are considered pro rata in the result analysis.



To achieve practically relevant strategy recommendations, the above ranking of impact factors requires further analysis and systematic grouping:

- The highest-ranked positive impact on the target factor is formed by “strong and long-term commitment from government”, for calibration purposes defined with an impact level of 100. The top-ranked negative impact factor – as its diametrical opposite – “fluctuating or unclear political support” has an impact strength value of 49. Further factors that require governmental involvement are “grid constraints”, “environmental pressure” and the resolution of “conflicts of interest”. Two lower-ranked statements concentrate on the regulatory process.
- The subsequently ranked impacts on the need to avoid “critical events regarding H&S (negative press)”, to “showcase commercial-scale projects / successful demonstrators” and to minimise “fragmented initiatives by unexperienced parties” led to the central conclusions drawn from this chapter that achieving the “array-scale success” is decisive. Apart from the mentioned “engineering challenge and the technology barriers” the detected “low ability of developers to work together” significantly hinder the development of the sector. The “collaboration and consolidation between companies” needs to be improved to avoid “failed demonstrations and technology failures” and to create a “satisfactory technology reliability record”.
- After proving the technological readiness by pilot and demonstration projects (i.e. the “array-scale success), it is necessary to lower the “high cost of devices / deployment” and to find a “cost-effective way to harvest marine energy”. The “lack of investor confidence” will thus be gradually reduced.

Table 13 groups the individual impact factors (strength of impact numbers in parenthesis) according to the above identified groups with similarities in their characteristics. The correspondingly formulated 3 milestone terms are shown in the right-hand column including the sum of the impact strengths in absolute figures and percentage values.

**Table 13: SD-model 1: Grouping of impact factors**

Grouped impact factors	Milestones
+ Strong and long-term commitment from government (100) – Fluctuating or unclear political support (49) – Grid constraints (20) – Environmental pressure (19) – Conflicts of interest (18) + Engagement industry / academia (17) – Regulatory requirement for project development (15) – Confused regulatory process / policy (10) + Climate change / price of carbon / decarbonisation (10) + Regulatory framework / regulatory support (5)	<b>No. 1</b> <b>Government support</b> (263 abs. / 48.5%)
– Critical events regarding H&S (negative press) (48) + Showcase commercial-scale projects / successful demonstrators (45) – Fragmented initiatives by unexperienced parties (23) – Failed demonstrations / technology failures (17) – Low ability of developers to work together (14) + Collaboration and consolidation between companies (13) + Development of international standards (9) – Engineering challenge / technology barriers (8) + Satisfactory technology reliability record (6)	<b>No. 2</b> <b>Array-scale success</b> (183 abs. / 33.8%)
– Lack of investor confidence (39) – High cost of devices / deployment (26) + Cost-effective way to harvest marine energy (20) + Proven O&M models (11)	<b>No. 3</b> <b>Cost reduction</b> (96 abs. / 17.7%)

The essence of the statements substantiating the milestones is formulated as follows:

(i) Government support

The leading impact factor “strong and long-term commitment from government” represents the foundation for progress in the sector and “fluctuating or unclear political support” is vital to the realisation of early-stage developments.

(ii) Array-scale success

The third and fourth strongest countervailing and reinforcing impact factors (“critical events regarding H&S (negative press)” and “showcase commercial-scale projects / successful demonstrators”) form the key elements of this interim milestone that triggers the subsequent stages of development.

(iii) Cost reduction

After having successfully demonstrated array-scale projects, the levelised cost of electricity will decline by serial manufacturing and technology convergence.

### **5.3 Calculated allotment of primary interview statements**

In the following, the expert interview statements constituting the positive and negative impact factors as identified by the system dynamics model 1 (Table 12) are referenced and put into context according to the determined milestone terms (Table 13).

#### **5.3.1 Government support**

The main threat to reach commercially viable power generation by marine energy is given by moving political positions. Fluctuating or unclear political support and “start-stop incentives” by governments are highly counterproductive. Fiscal measures to drive early-stage deployment and the implementation of the ROC mechanism in the UK are good examples that substantially support the positive development of the sector. Efficiently organised consenting, leasing and licensing processes within a clear regulatory framework support the technology development and de-risk pilot deployments. A number of interviewees communicated that in the past, consenting delays negatively influenced front-running project initiatives. In some cases, confused regulatory processes and a lack of appropriate marine spatial planning were reported.

As marine energy sites are in many cases located at the extremities of existing power grids, the excessive application of high transmission transfer charges and direct grid development cost negatively affect the sectorial development.

The motivation of societies to reduce environmental pressure and move towards sustainability are general driving factors for renewable generation projects. Global climate agreements and the gradual decarbonisation of power generation assets positively support the marine energy sector.

A hindering impact is caused by conflicts of interest. It was communicated that local environmental lobby groups are creating an increasing number of new restrictions on marine energy developments. The engagement of industry and academia requires further support on a public level with a focus on the harmonisation of research activities and technology development.

### **5.3.2 Array-scale success**

Providing confidence in the performance of the technological concept requires demonstrating commercial-scale projects. A central element in improving the device reliability is seen in the testing of full-scale prototypes at offshore test sites. The engineering challenge is significant and the technological barriers are high but will be stepwise reduced by the convergence of designs. With regard to the further required technology development and maturation, emphasis needs to be put on improving the device and system reliability. It is necessary to strengthen standardisation and to follow a gradual development approach.

Even as critical events in the course of the sectorial development might cause negative press, they need to be transparently communicated. Where there is no communication of failures in case of an incident, worst-case scenarios are imagined. Fragmented initiatives by unexperienced parties, the lack of industry success stories and failed demonstrations represent major negative impact factors.

Negative influences experienced in the course of the ongoing development of the sector are caused in part by the low ability of developers to work together and by the limited sharing of knowledge and experience. The lack of collaboration originates that “too many people are doing the same things”. Intensified collaboration between the manufacturing firms and knowledge transfer from other relevant industries (e.g. from oil & gas and offshore wind) support the development and progress. Positive effects are generated by the increasing commitment of OEMs and utility buy-ins (at the time of the interview series). Negative impact onto the development of the sector is caused by unrealistic timelines set by devices manufacturers and project developers and partly adopted by governmental bodies.

### **5.3.3 Cost reduction**

Regarding funding, it was emphasised that the renewable energy sector is characterised by a strong market with internal competition. Utilities have many options to invest (gas, solar, on-/offshore wind, etc.) and there is a certain distrust in the investment community. Without the necessary investor confidence, getting access to capital is difficult. The global economic situation and the continued financial instability negatively affect the investment climate.

The marine energy sector is characterised by a perception of high risk and cost combined with difficult stakeholder coordination. The “outrageously” expensive deployment and high cost of devices as well as long delays in projects coming on line are considered as counterproductive. Technology-related improvement efforts need to be directed towards re-establishing investor confidence and minimising the LCOE. The final objective is to find a cost-effective way (i.e. a techno-economic optimum) to harvest marine energy.

## **5.4 Sensitivity analysis and robustness of test results**

In the course of this analysis, the sensitivity and robustness of the initial system dynamics model is evaluated. The plausibility and reliability of the achieved results is verified in four steps by applying different methods:

- In an initial plausibility check, the original number of interview replies to each individual generic term is compared with the ranking of impact factors calculated by the modelling software. See paragraph 5.4.1 and Appendix E.1.4.1.
- In a second step, for the generic terms “showcase commercial-scale projects / successful demonstrators” and “lack of investor confidence” approximately 10% of respondents are removed and the model re-run. See paragraph 5.4.2 and Appendix E.1.4.2.
- Subsequently, one category of stakeholders (i.e. device manufacturers) is excluded in order to examine the corresponding impact on the modelling result output. See paragraph 5.4.3 and Appendix E.1.4.3.
- Finally, the impact time behaviour of the functional interconnections between the different elements is examined. To calibrate the research, all programmed time impact definitions are deleted, i.e. all correlations are uniformly defined as short-term. The impact factor ranking is compared with the ranking as per the number of interview replies. In the next examination, for the generic term “climate change / price of carbon / decarbonisation”, the originally configured time impact correlations are stepwise reduced from long- to mid- and short-term. The corresponding change in the result ranking is analysed. See paragraph 5.4.4 and Appendix E.1.4.4.

#### 5.4.1 Plausibility check: Ranking of interview replies and modelling results

The ranking of replies as per number of appearance to generic terms is compared with the ranking of generic terms calculated by SD-model 1. To streamline the analysis by excluding arguments of minor relevance, in Table 14 only generic terms with ranking values above 25 (either as per by the normalised interview reply value in Appendix E.1.4.1 or by the impact factor ranking in Table 12) are considered.

In column “Delta”, the allocated rank of each considered generic term is classified by comparing it to the SD-model 1 percentage values ( $\leftrightarrow$  stands for a practically identical ranking and each single arrow for  $\pm 15$  percentage points of difference).

**Table 14: Comparison of interview replies ranking and modelling results**

Generic term	Interview replies		SD-model 1	Delta
	[abs.]	[%]	[%]	
Strong and long-term commitment from government	45	100	100	$\leftrightarrow$
Fluctuating or unclear political support	17	38	49	$\uparrow$
Critical events regarding H&S (negative press)	2	4	48	$\uparrow \uparrow \uparrow$
Showcase commercial-scale projects / (...) demonstrators	10	22	45	$\uparrow \uparrow$
Lack of investor confidence	8	18	39	$\uparrow \uparrow$
High cost of devices / deployment	12	27	26	$\leftrightarrow$
Fragmented initiatives by unexperienced parties	5	11	23	$\uparrow$
Climate change / price of carbon / decarb. of gen. capacity	21	47	10	$\downarrow \downarrow \downarrow$
Engineering challenge and technology barriers	12	27	8	$\downarrow$

In order to principally verify the correct functioning of the numerical model, in a first step, all originally programmed time behaviour correlations were deleted. The respective system dynamics model can be found in Appendix E.1.4.4. In the corresponding comparison table, the modelling results are compared to the ranking of the interview data. As a result it can be concluded that the model reflects one to one the input data ranking in case where no time delay functions are programmed. Even the type of configuration and the number of group terms has no influence, as all impact strengths are calculated as per their ratio.

An exact match between the interview replies ranking and modelling results exist for:

- “Strong and long-term commitment from government” and “high cost of devices / deployment”. The first factor – the most significant – serves to normalise the interview data and to calibrate the modelling result analysis (insight matrix).

The following impact factors are ranked higher by the system dynamics simulation than their interview reply number ranking:

- As one of the very few impact factors configured in the SD-model, the impact time behaviour of “critical events regarding H&S (negative press)” is defined as “short-term”. This means it has immediate and thus in consequence stronger effect on the group term “encouraging marine operations experience” and on the final target, i.e. the development of the marine energy sector<sup>25</sup>.
- “Showcase commercial-scale projects / successful demonstrators” is ranked higher by the SD-model because it is configured as mid-term time relevant for all of the connecting 3 group terms out of which 2 connect to the final target with immediate effect. Within a model setup where a significant number of generic terms is correlated via long-term delayed impact functions and where 4 out of 7 connections from group terms to the final target are defined as undelayed, the apparent amplification effect can be explained.
- “Fluctuating or unclear political support” is slightly over-proportionally ranked by the SD-model due to the direct link between the group term “efficient consenting, leasing, licensing” and the final target.
- In the SD-model, the term “lack of investor confidence” connects with a mid-term effect to “encouraging marine operations experience” and directly to “appropriate project financing”. The immediate negative effect onto achieving financing is represented by the modelling result.
- “Fragmented initiatives by unexperienced parties” is higher ranked because it is considered as negatively affecting the business development with no delay.

---

<sup>25</sup> Background information: The reason to program this time impact relationship as undelayed is based on an experience made during the ICOE 2008 conference where setbacks regarding the stability and durability of a prototype tidal stream converter blade were intensively discussed between the scientists and experts. However, it was strictly avoided by the concerned leading device manufacturing firm to communicate the incident to public due to understandable reasons.

The following impact factors are ranked lower by the system dynamics simulation than their interview reply number ranking:

- The impact strength of “climate change / price of carbon / decarbonisation of generation capacity” is much lower ranked by the SD-model than interview ranking. This can be explained because 2 out of 3 connections to the correlated group terms are programmed with a long-term delay and additionally 2 out of 3 connections to the final target are programmed with mid-term delays. The reason for programming the delay functions as such is because the expected reinforcing impact (represented by the + sign in the SD-model) by the threat of climate change onto the final target is not new and there already exist mature and price-competitive renewable generation methods (e.g wind and solar PV). Consequently, the effect on the development of the marine energy sector is not considered as time critical and thus of minor relevance.
- Most replies (11 out of 12) under “engineering challenge and technology barriers” correlate via mid-term delay functions to the group term “consecutive technology learning” which itself connects to the final target in delayed manner. This is the reason for the lower ranking compared to the interview reply number.

#### Examination result

The differences in ranking between the system dynamics modelling results and the statistical distribution of the number of replies is exclusively originated by the programmed time delay functions between impact factors, group terms and the final target. Where no time delay functions are programmed, the interview data ranking is represented unaltered as shown in paragraph 5.4.4.

When comparing to a pure statistical ranking method by the number of replies, an inherent advantage of the SD-based modelling approach is emphasised as the inter factor correlation and time impact behaviour by a generic term can be individually configured which significantly increases the precision of the model and improves the reference to reality.



#### 5.4.2 Sensitivity analysis: Removal of subsets of sample population

The goal of this examination is to explore how the distribution of weightings and connections between the impact factors, group terms and the final target changes by the removal of subsets of population in the order of 4 to 18% (referring the number of replies to group terms). Selected for examination were the two impact factors “showcase commercial-scale projects / successful demonstrators” and “lack of investor confidence” because of their central relevance for the continuation of the research, as both are key elements of the milestones “array-scale success” and “cost reduction” as shown in Table 13. The full extent and background of the examination including all calculation details can be found in Appendix E.1.4.2.

##### Showcase commercial-scale projects / successful demonstrators

In the previously described original system dynamics model 1, the impact strength of the generic term “showcase commercial-scale projects / successful demonstrators” on the final target via different group terms is given as 45% (Table 14). As this generic term is connected to the final target via various group terms, all 3 correlations are examined one by one.

Dependant on the number of interview replies to the respective group term, parts of the sample population are removed in the order of -8 to -18%, as shown in Table 15. The impact on the rank-order of the individual generic term “showcase commercial-scale projects / successful demonstrators” is between -2 and -61% as shown in Appendix E.1.4.2.1 paragraph 1.1.2 and 1.3.2.

**Table 15: Removal of population: Reduction of replies to generic term #36**

Group term	Number of interview replies	Reduction of number of interview replies	Impact on target	
			[%]	[delta %]
Consecutive technology learning	Generic term: 2	Generic term: -100% (2 to 0)	44	-2
	Group term: 26	Group term: -8% (26 to 24)		
Confidence-building device operation experience	Generic term: 5	Generic term: -40% (5 to 3)	33	-36
	Group term: 11	Group term: -18% (11 to 9)		
Encouraging marine operations experience	Generic term: 3	Generic term: -67% (3 to 1)	28	-61
	Group term: 13	Group term: -15% (13 to 11)		

The principal output of the analysis summarised in Table 13 is not affected, as the second milestone “array-scale success” would comprise a value of 31.6% instead of 33.8%. The basic distribution of replies defining the 3 milestone terms is not affected.

Detailed explanations to the individual correlations:

- The first examined link to the group term “consecutive technology learning” is based on two interview replies and creates an impact strength of 45% (#36 in Table 12). When reducing the number of replies from 2 to 0 (-8% compared to the total of 26 replies to the group term as shown in Table 15), the impact strength becomes zero (arithmetically: 2 replies minus 10% from 26 replies). This is reflected on page 2/6 of Appendix E.1.4.2.1 by having removed the functional link between “showcase commercial-scale projects / successful demonstrators” and the group term “consecutive technology learning”. To correctly re-run the model, all other impact strength values feeding the respective group term and consequently the target factor have been re-calculated to guarantee a correct percentage-wise distribution. The consequential reduction of the impact strength onto the final target is calculated as 2%.
- Similarly, the impact strength on the second group term “confidence-building device operation experience” is reduced from 5 to 3 replies or -18% of the total number of 11 replies. The correspondingly calculated reduction in impact strength on the final target is 36%.
- The third link to “encouraging marine operations experience” experienced in the course of the simulation a reduction from 3 to 1 replies (or -15%) resulting in a reduced impact strength on the final target of 61%.

#### Lack of investor confidence

The original impact strength of the generic term “lack of investor confidence” on the final target via different group terms is given as 39% (Table 12).

Dependant on the total number of interview replies to the respective group term, parts of the sample population are removed in the order of -4 to -8%, which is shown in Table 16. The impact on the rank-order of the individual generic term “lack of investor confidence” is between -15 and -26% as shown also in Appendix E.1.4.2.2 paragraph 2.1.2 and 2.2.2.

**Table 16: Removal of population: Reduction of replies to generic term #24**

Group term	Number of interview replies	Reduction of number of interview replies	Impact on target	
			[%]	[delta %]
Appropriate project financing	Generic term: 7 Group term: 47	Generic term: -29% (7 to 5) Group term: -4% (47 to 42)	31	-26
Encouraging marine operations experience	Generic term: 1 Group term: 13	Generic term: -100% (1 to 0) Group term: -8% (13 to 12)	34	-15

The third milestone “cost reduction” in Table 12 would comprise a value of 16.5% instead of 17.7%. The basic distribution of replies defining the 3 milestone terms is not affected. As the generic term “lack of investor confidence” is connected to the final target via 2 group terms, both correlations are examined as follows:

- The undelayed link to the group term “appropriate project financing” is based on originally 7 interview replies creating an impact strength of 14%. When reducing the number of replies from 7 to 5 (-4% regarding the total number of replies of the group term of 47) the impact strength on the final target decreases by 26%.
- The “encouraging marine operations experience” link is programmed with a mid-term delay function. A reduction of the number of interview replies from 1 to 0 (link deleted in SD-model based on reduction of -8% considering the total number of 12 replies) leads to a reduction of the impact onto the final target of 15%.

### Examination result

All five examinations confirm the stability of the system dynamics model 1 and the reliability of the calculated results. The model does not show any non-linearities and the principal conclusions remain unaltered by the sensitivity tests.

The correlation between the reduction of numbers of replies to a group term and the consequence on the final target is directly related to the programmed time delay characteristics. The performed reduction of the number of replies, even those leading to the deletion of functional interconnections, keep the model stable. The impact on the final target of full-commercial power generation differs dependent on the simulated reduction of replies and the type of interconnections from the generic terms to the final target. As such, the correlation between the reduction of replies and the consequences on the impact on the final target is not proportional. The principal output of the research on the grouped impact factors shown in Table 13 is not affected.

### 5.4.3 Sensitivity analysis: Removal of one category of stakeholder

This examination explores how the distribution of weighting factors and functional connections change by the removal of one category of stakeholder.

In the course of identifying which stakeholder group to eliminate for the analysis, the decision was taken to exclude the device manufacturer group. The reason was that they feature in a relatively high number of replies (36 out of 234, the second strongest group after “government associations” with 54 replies) as shown in Appendix E.1.2.1. Of similar importance is the fact that this group has the highest financial interest in rapidly commercialising marine energy in order to compensate the significant investments made in the past.

Without the interview replies of this stakeholder group, several generic terms experience a significant (defined as  $\geq 7$  percentage points) increase or decrease in their impact strength on the final target of full-commercial generation. Reference is made to Appendix E.1.4.3 paragraph 4 where the modified input data table with SD-model 1, the corresponding insight matrix and a result overview table can be found.

The following observations can be made:

- Even though the most significant change (-17 percentage points) in the ranking of the impact factors is for “critical events regarding H&S (negative press)”, it needs to be taken into account that only 2 interviewees mentioned this factor and that the high relevance is driven by the programmed undelayed impact on the correlated group term “encouraging marine operations experience”.
- The second most important alteration relates to “conflicts of interest”. The significance of this generic term increases by 10 percentage points where device manufacturers are not considered. As the natural interest of device manufacturers lies in selling their products, they might consciously underrate potential conflicts of interest with fishery, offshore wind, military, shipping routes and tourism as this is not under their direct responsibility.
- Without the participation of the device manufacturers, generic terms like the need to “showcase commercial-scale projects / successful demonstrators” as well as disadvantages by “fragmented initiatives by unexperienced parties” experience

higher significance (+9, respectively +7 percentage points). The reason might relate to the reported statement that “the industry presented itself as being at a more advanced state of development than it really was”. In similar manner, it can be explained why the need to strengthen the “engagement industry / academia” is higher rated without the input of the device manufacturers.

Considering the present pre-commercial situation and the need to overcome it, it is surprising that aspects like “grid constraints” and “lack of investor confidence” experience higher consideration without the replies from the device manufactures. Nevertheless, due to the principally low number of replies behind most singular generic terms, the global outcome and definition of key milestones are more important in this part of the research.

### Examination result

The maximum impact on each generic term and on the interim milestone of achieving the “array-scale success” is given in Appendix E.1.4.3.4 paragraph 2.

The key contribution of this chapter lies in the traceable determination of the key milestones necessary to efficiently commercialise power generation by marine energy technologies. The overall impact on the definition of the milestone terms by excluding the interview input data provided by the 30 device manufactures is insignificant. The principal definition of the 3 consecutive milestones “government support”, “array-scale success” and “cost reduction” as shown in Table 13 is not touched. Nevertheless, without the opinion of the device manufacturers, a slight shift in the ranking of milestones terms can be detected: The interim milestone “array-scale success” experiences a reduction in significance of 1.5 percentage points.

As the importance of the milestone is higher rated without the device manufacturers’ input, it can be interpreted that this group prefers to continue with their own strategy and time planning, which is not in favour of the overall development sector.

The stability of the model and the reliability of the calculated results are confirmed.

#### **5.4.4 Sensitivity analysis: Impact by determination of time behaviour**

As concluded previously, the programmed time correlations between the different factors principally define the results calculated by the simulation software. Consequently, in this examination, the time behaviour is examined in detail.

First, it is investigated how the model behaves when all time correlations are deactivated, i.e. in this case defined identically as short-term.

In a second step, for a specific example, the originally configured time impact correlations are stepwise reduced from long- to medium- and finally in a uniform manner to short-term. The corresponding change in the result ranking is analysed. Reference is made to Appendix E.1.4.4.

##### SD-model 1 without programmed time impact definitions

For this examination, all impact correlations between the generic terms, group terms and the final target are configured in neutral manner, i.e. uniformly defined as short-term impact. Similar conclusions would be achieved by defining all as mid- or long-term as the only relative difference is important here.

The subsequently achieved ranking of impact factors is identical to the ranking of interview replies (Appendix E.1.4.1) when excluding rounding effects or minor reading errors at graphical representations.

##### Gradual modification of programmed time behaviour

The objective of this examination is to verify how the ranking (i.e. the impact strength on the final target of full-commercial power generation) of a generic term changes when gradually tightening its time impact behaviour from long to short-term. The reason for examining the aspect of “climate change / price of carbon / decarbonisation of generation capacity” (generic term #2) is given by the overall importance of this global aspect and the calculated low ranking as in paragraph 6.4.1.

Table 17 shows the stepwise configuration change from a delayed factor (2 out of 3 connections were defined as long-term) towards uniformly short-term.

**Table 17: Stepwise modification of time impact behaviour**

Group term			Impact on final target		
Appropriate project financing	Efficient consenting, leasing, licensing	Consolidated business development	Original [%]	Modified [%]	Change [% points]
Long-term	Long-term	Mid-term	10	-	-
Mid-term	Long-term	Mid-term	10	12	2
Mid-term	Mid-term	Mid-term	10	28	18
Short-term	Mid-term	Mid-term	10	46	36
Short-term	Short-term	Mid-term	10	132	122
Short-term	Short-term	Short-term	10	189	179

The ranking values show how the relevance of the examined generic term “climate change / price of carbon / decarbonisation of generation capacity” gradually increases by tightening the time impact correlation. Starting at the fourth modification, the considered generic term becomes the most important impact factor (122%).

#### Examination result

It is noteworthy that the type of network configuration itself (e.g. connection of one generic term to one or more group terms) has no influence on the impact strength results, as these values are calculated by per factor distribution. Apart from the percentage-wise definition of the impact strength according to the interview replies, the definition of the time behaviour is decisive for achieving reliable results.

The examination shows that the computer model works in a stable manner and that the calculated results are achieved in a traceable manner.

#### **5.4.5 Assessment of the sensitivity and robustness of the model**

After successfully verifying the principle of the results by comparing the number of interview replies per generic term to the ranking by the computer modelling, sample populations were gradually removed. Furthermore, the reliability of the model was confirmed by removing one group of stakeholders leading to comprehensible changes in the results. A final examination confirmed the basic importance of realistically defining the time impact behaviour. Where time impact is not defined, the results are fully congruent with the statistical distribution of the primary interview replies.

In the course of examining the sensitivity of the system dynamics model and confirming the robustness of the results, a key advantage of the chosen approach was underlined: the important possibility to specifically define the time correlation between the individual factors, also by further splitting them into precise group terms.

## 5.5 Chapter summary

The following conclusions are drawn from the chapter:

- For orienting the marine energy development trajectory, the identification of essential impact factors and the determination of pivotal milestones is required.
- The highest-ranked impact factors on the target of commercial power generation are “strong and long-term commitment from government” and the diametrically opposite “fluctuating or unclear political support”. The second-ranked countervailing impact factor on critical events regarding H&S and negative press forms, together with the reinforcing impact factor to “showcase commercial-scale projects/successful demonstrators”, the central elements for achieving “array-scale success” which will trigger the further development of the sector. After having successfully demonstrated array-scale schemes, the LCOE will decline due to serial manufacturing and technology convergence processes.
- The consecutive milestones for reaching commercial generation are (i) Government support; (ii) Array-scale success; and (iii) Cost reduction.
- As the singular characteristics of government support have been extensively studied, they are deemed outside of the range of this research. Focus is therefore put on the interim milestone “array-scale success”.
- In the course of the sensitivity analysis and the testing of the robustness of results, it was found that the definition of the time impact behaviour is of highest relevance for achieving reliable results. A number of plausibility checks and modifications in the model configuration confirmed robustness of the model and the reliability of the basic research approach.
- The next step in the research effort will be to investigate what is needed to successfully achieve the “array-scale success”.



## **6 THE GAME-CHANGING “ARRAY-SCALE SUCCESS”**

In the previous chapter, it was identified that a key milestone on the way towards reaching full-commercial power generation is to achieve “array-scale success”. Hereto, the demonstration of one or more successful near-commercial projects is required. Passing the interim milestone will create confidence in the technology and de-risk future investments.

This chapter focuses on identifying the strategies and requirements to approach and pass this decisive milestone.

### **6.1 Necessity for SD-model 2**

As the singular characteristics of government regulations are outside the range of this research, focus is on the previously identified second-ranked milestone “array-scale success”. The effective preparation and management of this decisive constituent is seen as the key task at the present stage of development.

The term “array-scale success” stands for one or more pilot projects that can serve as a blueprint with a close-to-commercial project setup and mature implementation characteristics. As a formal element of the marine energy market breakthrough, transparent insight into the key performance indicators of such projects is required, for example information about the procurement method, CapEx and OpEx data, capacity factor and energy yield data as well as experienced setbacks and delays. An independently certified successful 1-year commercial operation period is considered as minimum to assess a project.

In the course of the interview series, the importance of focussing on “array-scale activities” and the need to “get pilot farms built” was repeatedly stressed. Most answers to the question “In which areas is research most required to accelerate the development of marine energy?” directly referred to multi-device arrangements such as “array-scale design”, “hydrodynamic modelling of arrays”, “array-scale maintenance”, “the need for design tools to facilitate cost-effective array-scale development” and “to see first arrays progress through FID<sup>26</sup>”.

---

<sup>26</sup> Final Investment Decision (see “FID enabling for renewables” by the Department of Energy & Climate Change, UK).

With the near-future prospect of realising individual profit in a newly created power market segment, there should be a strong motivation for cooperative industry interaction aiming for jointly de-risking the technology and rapidly achieving the market breakthrough.

The identified prioritised strategy options help to efficiently prepare and manage the “array-scale success” and thus to achieve a step change in the development of marine renewables.

## **6.2 Showcase commercial-scale projects / successful demonstrators**

### **6.2.1 Definition of target factor**

In this higher focussed model, the previously identified need to “showcase commercial-scale projects / successful demonstrators” – as the central element for achieving “array-scale success” – serves as new target factor.

The intention behind the SD-model is to identify the top-level driving factors for achieving this interim milestone and thus to enable the market breakthrough.

### **6.2.2 Reference to questionnaire**

The model is based on the replies to below questions in Appendix B.2:

- # 2.1 Which are most valuable experiences gained by early movers in marine energy?
- # 2.2 Which lessons learnt in offshore wind can be transferred to marine energy?
- # 2.3 Which lessons learnt in oil & gas can be transferred to marine energy?
- # 2.4 Knowledge from which sectors might be useful to achieve full commercialisation?
- # 3.2.2 Which should be top-priority tasks (in government) to reach commercialisation?
- # 4.1 Where do you see concerns for delays and cost overruns in marine energy?
- # 4.2 Where do you see potential to get cost for utility-scale implementations down?
- # 4.3 What are the main factors driving up the insurance cost?
- # 4.4 What measures can be taken to avoid experienced cost increase in offshore wind?

### **6.2.3 Group terms / sub-group terms / generic terms**

In total, 26 generic terms were defined in the course of conditioning the replies (Table 18). After a first sorting into 8 sub-group terms, the replies were allocated question-wise to three key topic areas, represented in the SD-model as group terms. The group terms are either fed directly by the interview replies or via sub-group terms.

#### **6.2.4 Model configuration**

For the configuration of the computer model, 671 individual replies were considered.

The system dynamics model in Fig. 7 is composed in a concentric manner around the target factor according to the key topic areas for harnessing the potential of marine energy, named by McSweeney (2012) as: technology, policy and financing. In a similar manner, Magagna and Uihlein (2015) described that marine energy faces four main bottlenecks: technology development, finance and markets, environmental and administrative issues as well as grid availability. When assigning environmental issues to the policy domain and allocating the administrative needs to the individual players, then both classification systems fit.

In the right-hand middle area, the target factor is located, which is fed by the 3 main nodes, i.e. group terms:

- Knowledge transfer and learning for neighbouring sectors (“technology”).
- Top-priority tasks in the work of government agencies (“policy”).
- Having costs under control (“financing”).

#### **6.2.5 Polarity of relationship and time behaviour**

To simplify the interpretation of the SD-model configuration, for all generic terms, sub-group and group terms positive formulations (or ones with a basic supporting attitude) were used, such as “top-priority tasks”, “knowledge transfer and learning”, “having costs under control” as well as for example “most valuable experiences”, “lessons learnt”, “knowledge from other sectors”, “minimising delays” and “avoid cost increase”. Consequently, all correlations from the generic terms via the sub-group and group terms up to the target factor are uniformly defined with positive polarities.

No individual time delay factors were defined.

**Table 18: SD-model 2: Group terms, sub-group terms and generic terms**

<b>Group terms</b>	<b>Generic terms</b>
Sub-group terms	
<b>Top-priority tasks in the work of government agencies (“policy”)</b>	
	Device operation experience; Project structuring, project / risk management and EIA; Project financing; Business development; Technology learning; Consenting, leasing, licensing.
<b>Knowledge transfer and learning for neighbouring sectors (“technology”)</b>	
Most valuable experiences by “early movers”	Marine operations experience; Device operation experience; Project financing; Business development; Technology learning; Consenting, leasing, licensing; Reduction of CapEx and OpEx, Negotiation experience to share risks.
Lessons learnt in offshore wind industry	Working at sea in hostile conditions (access, installation, vessel, logistics); Manage an array full of assets and operate it 24/7; Subsea cabling lay, interconnections, grid interface and network operation; Project structuring, project / risk management and EIA; H&S; Reduction of CapEx and OpEx; Improving reliability (offshore structures, materials, fatigue, electronics); Consenting, leasing, licensing.
Lessons learnt in oil & gas industry	O&M strategies and methods; Oil & gas bespoke technology, one-off solutions, “big problems, big money”; 24/7 subsea marine operations, installation, deployment, ROVs; Project structuring, project / risk management and EIA; H&S; Reduction of CapEx and OpEx; Marine technology (design, integrity, material, corrosion, bio-fouling); Risk sharing contractually optimised.
Knowledge from other sectors useful to achieve commercialisation	Offshore wind or other maritime affairs; Conventional power generation (hydro, thermal, nuclear); Shipbuilding; Aerospace and defence; Initial marine energy deployments; Aquaculture and environment; Information technology; Serial production industry.
<b>Having costs under control (“financing”)</b>	
Minimising delays and cost-overruns.	Marine operations experience; Device operation experience; Project structuring, project / risk management and EIA; Project financing; Business development; Reduction of CapEx and OpEx; Technology learning; Consenting, leasing, licensing.
Potential to get cost for utility-scale project implementation down.	
Main factors to limit insurance cost.	
Measures to avoid experienced cost increase in offshore wind.	

## 6.2.6 Causal diagram

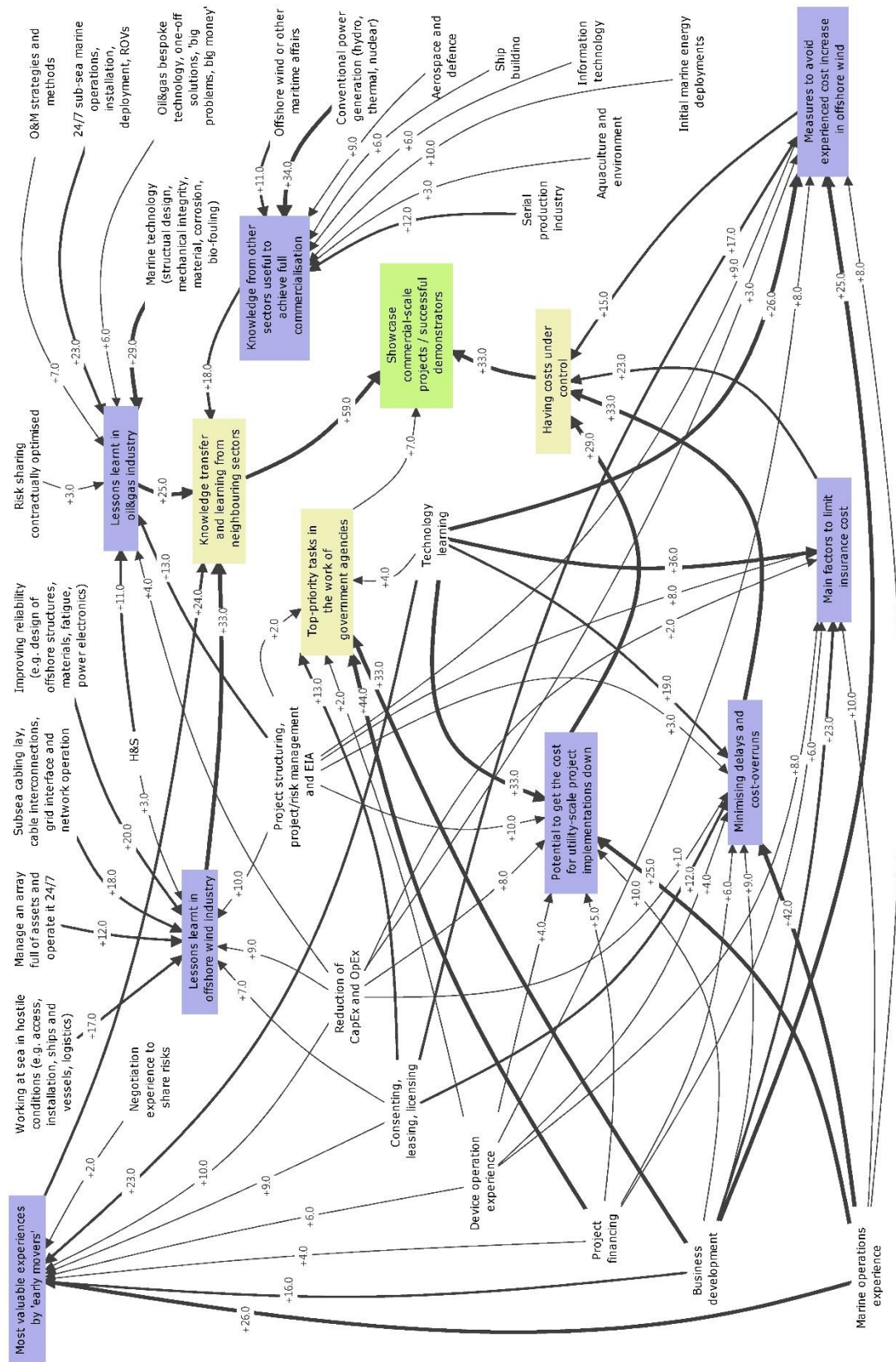
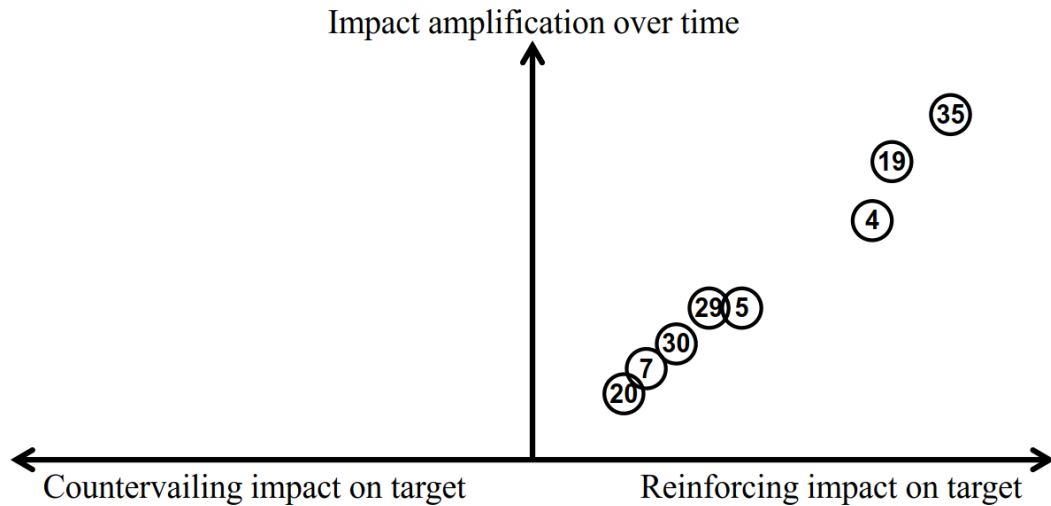


Fig. 7: SD-model 2: Showcase commercial-scale projects / successful demonstrators

### 6.2.7 Insight matrix and ranking of top-level driving factors

To remain with the x-axis designation as for model 1 (Fig. 6), the results of the reinforcing model 2 are displayed graphical on the right-hand side in Fig. 8 (reference is made to Appendix E.2.2).



**Fig. 8: SD-model 2: Insight matrix**

In Table 19, the item numbering in the insight matrix is explained (see “#”) and the top-level driving factors identified by SD-model 2 “Showcase commercial-scale projects / successful demonstrators” are numerically ranked.

**Table 19: SD-model 2: Ranking of top-level driving factors**

	<b>Ranking</b>
Technology learning (#35)	100
Marine operations experience (#19)	86
Business development (#4)	77
Consenting, leasing, licensing (#5)	49
Project structuring, project / risk management and EIA (#29)	44
Reduction of CapEx and OpEx (#30)	35
Device operation experience (#7)	27
Marine technology (#20)	21

The by far strongest impact factors on the target of showcasing commercial-scale projects are identified as “technology learning” (for calibration purposes defined with an impact level of 100), followed by “marine operations experience” (86) and “business development” (77).

### **6.3 Calculated allotment of primary interview statements**

The two top-ranked risks for the realisation of tidal current or wave power projects were statistically ranked by direct replies or the interviewees as “reliability” and “achieving funding” (Table 8). As funding is required for improving reliability (and vice-versa), the two risks complexes are directly interlinked. Achieving the “array-scale success” represents a game-changer because both risk complexes will be simultaneously mitigated. The “array-scale success” finds itself in the centre of the area of conflict between reliability and achieving funding. Coordinated action is required to overcome this circular relationship (“chicken or egg causality dilemma”).

Passing this milestone will demonstrate the maturity of the technology. Future investments will be de-risked and the additionally gained investor confidence will facilitate the market breakthrough. In case the first arrays do not deliver good results and acceptable financial returns, the focus of investor interest might shift to other forms of renewable generation. The significant public and industry investment made might not be compensated.

Based on the ranked questions in paragraph 6.2.2, corresponding interview statements substantiating the need to showcase successful demonstrators were extracted from the database. Representative interview arguments that underline the need to achieve the “array-scale success” and thus to facilitate the market breakthrough are presented in a compressed manner oriented along the ranking of top-level drivers factors in Table 19.

#### **6.3.1 Technology learning (#35)**

“Reliability”, as one of the two top-ranked risks identified in the course of the survey, represents the central element of generic term “technology learning”. A US academic named the need for longer baselines for system reliability and an R&D vice-chair even outlined that reliability is more important than efficiency. A gradual improvement in reliability, durability and survivability through testing designs in the marine environment is seen as essential to strengthen technology confidence. More focus should be put on reliability in the system design by using reliability modelling techniques and applying the systems engineering approach. It is necessary to minimise the uncertainty regarding the technology performance and to focus on technology

readiness. Due to the many unknowns in developing marine energy projects, the chance to achieve commercial return is seen as seen as questionable.

Real site measurements are required to better understanding the resource and to more accurately calculate the energy yield, i.e. the estimated annual energy production. The relevance of having access to methods for reliably identifying the most efficient and less-conflicted marine sites, already in early project stages, was underlined.

Without assured grid connection, no project will go ahead. Major complexities are mentioned with regard to subsea cabling and the grid interconnection. Delays to vital electrical infrastructure upgrades have an impact on marine energy construction schedules and cause costs to rise. Areas of greatest resource are often located far away from population centres.

Bringing in offshore oil & gas marine operation expertise is seen as essential. Some interviewees emphasised that shared learning and a better exchange of engineering and environmental data can prevent the same mistakes being made time and again. Lessons learned between projects must be shared.

The need to foster collaboration and to bring in industrial expertise from offshore wind and other sectors is required to achieve technology transfer. A higher level of cooperation between project and technology developers is required to minimise replication and duplication in the manufacturing process. Cooperation between project developers, also dealing with different forms of renewable generation, might also include sharing the grid connection between multiple projects.

Setting up a comprehensive risk management process helps to create a solid evidence base by reducing uncertainties and transparently proving the technology. Due to the partly experimental nature of marine energy, techno-economic limitations should be considered within risk management.

### **6.3.2 Marine operations experience (#19)**

The importance of life cycle oriented testing of equipment in real conditions as well as gaining offshore deployment experience has been underlined several times. It is acknowledged that the harsh environment triggers iterative design and build approaches.



Limited work windows due to extreme weather conditions and difficult logistics contribute to the challenge of operating in the marine environment. Direct experience of cost overruns due to weather-induced delays was reported. Apart from the proximity of port infrastructure and the availability of shipyards, access to lower cost installation vessels is essential. Due to the competition with the oil & gas industry or the offshore wind sector, the availability of heavy marine services or DP vessels can be restricted.

By using experience gained in oil & gas exploration and by the heavy machinery or even the defence industries can help to avoid that mistakes are not repeated. A previous underestimation of marine operations challenges was communicated. In contrast to offshore wind, tidal current and wave power technology does not benefit by extension from reliable onshore devices.

### **6.3.3 Business development (#4)**

The interviewees were of the opinion that intensified collaboration between OEMs and project developers contains great potential for advancing the marine energy sector. The commercial proof of concept is a prerequisite for the market entry and represents the central management target. Apart from the general interest in bringing the technology rapidly to market, some interviewees consider an early market entry as critical. They argue that in case long-term device reliability expectations are not met, reputational damage or warranty claims could result.

It is expected that supplier competition will be further intensified, driven by serial production expected to commence after the market breakthrough. Nevertheless, the communicated inability of device developers to supply multiple devices on time and budget due to the minor scale of the industry, will be become resolved and monopoly supply restrictions for key components will end.

If the marine energy risk level can be reduced, insurance companies might have to refrain from their safe margins policy, presently explained by the very limited marine energy insurance market.

A sequential application of “push-pull mechanisms” was recommended: (i) technology-push strategies typically required for breakthrough innovations and thus to create a new market; and (ii) market-pull strategies for large-scale deployment while enabling further incremental innovation.

#### **6.3.4 Consenting, leasing, licensing (#5)**

The planning system is often seen as complicated and time delaying. The necessity to streamline the permitting (e.g. for a grid connection) was emphasised. The agencies need to implement government policy without unnecessary bureaucracy.

Positive experience regarding the license application process at regulatory bodies was made with the concept of a single point of handling. It was unanimously agreed that licensing has been greatly simplified by this in the last few years.

The importance of early engagement with regulatory authorities was underlined, as failing to do so can cause significant project implementation delays.

#### **6.3.5 Project structuring, project / risk management and EIA (#29)**

In the first place, the interviewees underlined that the need to understand that marine energy is a risky business and that in the past a general underestimation of risks and uncertainties could be detected.

Some interviewees referred to experience with the inadequate handling of projects. Project management needs to be clear on strategy and as one element thereof, a coordinated approach to collect data on failures is considered as relevant. The ability to quantify risk can be improved by following a structured engineering process.

Synergies are expected by coupling different kind of renewables. Positive effects are furthermore expected by standardised contract structures and by the application of collaborative contracting.

#### **6.3.6 Reduction of CapEx and OpEx (#30)**

It needs to be accepted that marine infrastructure and offshore intervention are expensive. Interviewees explained that high cost are associated with deployment, O&M and failure correction activities.

The cost of electricity production depends on the capacity deployed and, according to statistics, are directly related to water depth and distance to shore.

It was recommended to focus on LCOE and not on CapEx. Even optimum LCOE might involve higher CapEx by using higher quality components and applying a certain degree of over-engineering. Pushing down on CapEx in isolation is

counterproductive. The idea of trading-off cost and reliability was mentioned. In order to become an attractive investment opportunity, marine energy needs to urgently gain commercial experience and to reduce cost. Investors require clarity where to invest.

#### **6.3.7 Device operation experience (#7)**

Pilot projects are essential to provide availability records and to gain O&M experience of assets. It needs to be proven that the converters and ancillary systems work reliably.

Focus must be on array-level design and on system integration.

#### **6.3.8 Marine technology (#20)**

The need to improve the mechanical integrity of the devices and to strengthen component standardisation was mentioned. Focus must be put on extreme engineering and on the design for reliability and survivability. The equipment and components must withstand the harsh marine conditions. Appropriate materials that allow control of corrosion and bio-fouling have preference.

Relevance is given to connection and disconnection interface systems to ease the replacement of components. Special attention needs to be given to submerged structures, i.e. the foundation design and geotechnical analyses.

### **6.4 Chapter summary**

The following conclusions are drawn from the chapter:

- The marine energy market breakthrough and thus the proof of the commercial viability depends on demonstrating one or more close-to-commercial projects by which the interim milestone “array-scale success” will be achieved.
- There is a circular relationship between the two major risk complexes, reliability and funding, which needs to be resolved as a prerequisite for the market breakthrough. By showcasing the “array-scale success” concerns about reliability will disappear and project funding will be released.
- A (temporary) joining of forces is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence.

- In case the first arrays do not deliver good results and acceptable financial returns, the focus of investor interest might shift to other forms of renewable generation. The significant public and industry investment made might not be compensated.

In order to make full use of the interview data record and to further substantiate the achieved findings, it is beneficial to take a diametrically opposite target perspective and to focus on the factors that negatively influence the development of the marine energy sector. This will be the focus of the next chapter.

## **7 NEGATIVE IMPACT ON THE DEVELOPMENT**

The results achieved in the previous chapter regarding the identification of top-level driving factors necessary for achieving the “array-scale success” are a good foundation for strategy-finding. Nevertheless, it is required to consolidate the findings by cross-checking them with negative impacts acting on the development of the sector. By combining and balancing both the positive and negative impacts, harmonised stakeholder-specific strategy options can be elaborated in a concise manner.

### **7.1 Necessity for SD-model 3**

To substantiate the research by processing further insight gained by the expert interviews, in this system dynamics model, all negative impact factors hindering, delaying or countervailing the development of the marine energy sector are integrated.

### **7.2 Negative impact on development of marine energy**

#### **7.2.1 Definition of target factor**

In order to make full use of the interview data record and to cross-check the results achieved by SD-model 2, in this chapter a diametrically opposite perspective is taken to configure a third SD-model by identifying and analysing the ranking of exclusively negative impacts.

As such, the new target factor was defined as “Negative impact on the development of marine energy”.

#### **7.2.2 Reference to questionnaire**

The model is based on the replies to below questions and topics in Appendix B.2:

**# 3.1.2 Which internal targets appeared more difficult to reach than originally planned?**

**# 3.1.4 What are main reasons why marine energy has not developed more rapidly?**

**# 6.1 Which are the key risks in commercial-scale marine energy per project phase?**

**# 6.2 Risk transfer or risk propagation.**

**# 6.3 Please correlate each risk type to an estimated risk level.**

### 7.2.3 Group terms / sub-group terms / generic terms

Each of the above referenced 5 questions or topics forms one group term as per Table 20. The defined sub-group terms follow standard allocations used several times in this research, i.e. by the definition of risk categories (strategic, financial, technological) or by project stages (project initiation and concept, planning and design, manufacturing and testing, erection and commissioning, commercial operation, decommissioning).

Out of the high number of interview replies, a small group of 20 generic terms was defined, feeding the 5 group terms either directly or via interim nodes (i.e. by sub-group terms).

**Table 20: SD-model 3: Group terms, sub-group terms and generic terms**

Group terms	Generic terms
Sub-group terms	
<b>Difficulties in reaching internal targets.</b>	Marine operations experience; Device operation experience; Project structuring, project / risk management and EIA; Project financing; Business development; Reduction of CapEx and OpEx; Technology learning; Consenting, leasing, licensing.
<b>Slow development of marine energy sector.</b>	
<b>Critical risk transfer or risk propagation processes.</b>	
<b>Multiple demands by risk complexes</b>	
Strategic risks	Regulatory issues, Environmental impact, Conflicts of use, Infrastructure and logistics, Project management, Regulatory issues, Environmental impact.
Technological risks	Ambient requirements, Energy conversion system, Power export, Operational risks.
Financial risks	Funding requirement, Profitability requirement, Insurance requirement.
<b>Key risks in commercial-scale marine energy per project phase</b>	
Problems with project initiation and concept	Marine operations experience; Device operation experience; Project structuring, project / risk management and EIA; Project financing; Business development; Reduction of CapEx and OpEx; Technology learning; Consenting, leasing, licensing.
Difficulties in planning and design	
Challenging manufacturing and testing	
Challenging erection and commissioning	
Disturbance of commercial operation	
Unclear decommissioning	

Policy-related tasks are summarised under the generic term “consenting, leasing, licensing”. Aspects with reference to the financing sector are considered under “reduction of CapEx and OpEx” and “funding requirement”.

#### **7.2.4 Model configuration**

For the configuration of this model, 1,712 individual replies were evaluated. The reference questions reflect stakeholder-wide experience and setbacks suffered.

As shown in Fig. 9, the model is composed around the target factor “negative impact on the development of marine energy”, located in the right-hand middle area.

#### **7.2.5 Polarity of relationship and time behaviour**

For all sub-group and group terms, formulations with negative polarity, or indicating a basic problem, are used. For the group terms, formulations can be found like “difficulties in reaching internal targets”, “slow development of marine energy sector”, “critical risk transfer or risk propagation processes”, “multiple demanding by risk complexes” or “key risks in commercial-scale marine energy per project phase”. For the sub-group terms, further characteristic terms such as “unclear”, “disturbance”, “challenging”, “difficulties” and “problems” were used.

Consequently, all correlations between the 5 group terms and the single target factor are defined with positive polarities (“the independent and dependent variable change in the same direction”). Negative impact by the group-terms is directly forwarded onto the (also negatively formulated) final target.

All individual generic terms are formulated in a neutral or positive manner so that they act with inverse effect (negative polarity) on the sub-group or group terms.

No individual time delay factors were defined.

The diagram illustrates the complex relationships between various risk categories and their impacts on marine energy projects. The nodes are color-coded and connected by arrows with numerical values representing the impact.

**Blue Nodes (Critical "risk transfer" or "risk propagation" processes):**

- Difficulties in reaching internal targets
- Slow development of marine energy sector
- Critical "risk transfer" or "risk propagation" processes
- Multiple demands by risk complexes
- Key risks in commercial-scale marine energy per project phase

**Yellow Nodes (Risk Categories):**

- Strategic risks
- Financial risks
- Technological risks
- Problems with project initiation and concept
- Difficulties in planning and design
- Challenging manufacturing and testing
- Challenging erection and commissioning
- Disturbance of commercial operation
- Undeared decommissioning

**Green Node (Negative Impacts):**

- Negative impacts on the development of marine energy

**Other Nodes:**

- Regulatory issues
- Environmental impact
- Conflicts of use
- Infrastructure and logistics
- Project management
- Funding requirement
- Profitability requirement
- Insurance requirement
- Ambient requirements
- Energy conversion system
- Power export
- Operational risks
- Marine operations experience
- Device operation experience
- Project structuring, project/risk management and EIA
- Project financing
- Business development
- Reduction of CapEx and OpEx
- Technology learning
- Consenting, leasing, licensing

**Key Connections and Values:**

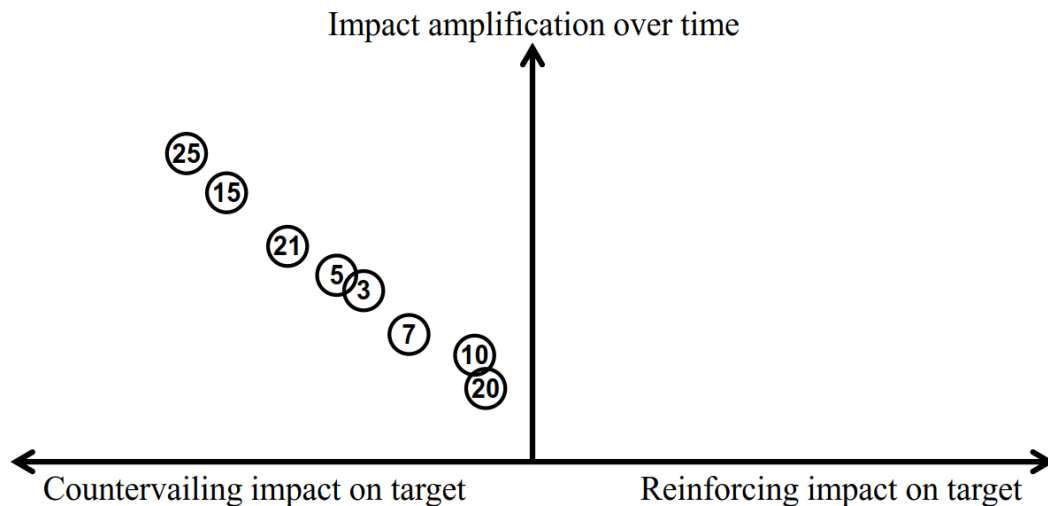
- Difficulties in reaching internal targets → Multiple demands by risk complexes (+10.0)
- Slow development of marine energy sector → Multiple demands by risk complexes (-8.0)
- Multiple demands by risk complexes → Strategic risks (+39.0)
- Multiple demands by risk complexes → Financial risks (+28.0)
- Multiple demands by risk complexes → Technological risks (+32.0)
- Strategic risks → Regulatory issues (-19.0)
- Strategic risks → Environmental impact (-16.0)
- Strategic risks → Conflicts of use (-22.0)
- Financial risks → Infrastructure and logistics (-39.0)
- Financial risks → Project management (-31.0)
- Financial risks → Funding requirement (-23.0)
- Technological risks → Profitability requirement (-25.0)
- Technological risks → Insurance requirement (-26.0)
- Technological risks → Ambient requirements (-24.0)
- Multiple demands by risk complexes → Negative impacts on the development of marine energy (+25.0)
- Negative impacts on the development of marine energy → Problems with project initiation and concept (+30.0)
- Problems with project initiation and concept → Difficulties in planning and design (+19.0)
- Problems with project initiation and concept → Challenging manufacturing and testing (+16.0)
- Problems with project initiation and concept → Challenging erection and commissioning (+17.0)
- Difficulties in planning and design → Challenging manufacturing and testing (-21.0)
- Difficulties in planning and design → Challenging erection and commissioning (-13.0)
- Challenging manufacturing and testing → Challenging erection and commissioning (-7.0)
- Challenging erection and commissioning → Disturbance of commercial operation (-13.0)
- Disturbance of commercial operation → Undeared decommissioning (-22.0)
- Undeared decommissioning → Key risks in commercial-scale marine energy per project phase (+10.0)
- Key risks in commercial-scale marine energy per project phase → Operational risks (+17.0)
- Key risks in commercial-scale marine energy per project phase → Energy conversion system (+17.0)
- Key risks in commercial-scale marine energy per project phase → Power export (+16.0)
- Key risks in commercial-scale marine energy per project phase → Insurance requirement (+19.0)
- Key risks in commercial-scale marine energy per project phase → Profitability requirement (+20.0)
- Key risks in commercial-scale marine energy per project phase → Funding requirement (+23.0)
- Key risks in commercial-scale marine energy per project phase → Infrastructure and logistics (+25.0)
- Key risks in commercial-scale marine energy per project phase → Conflicts of use (+22.0)
- Key risks in commercial-scale marine energy per project phase → Environmental impact (+16.0)
- Key risks in commercial-scale marine energy per project phase → Regulatory issues (+19.0)
- Marine operations experience → Project structuring, project/risk management and EIA (-10.0)
- Device operation experience → Project structuring, project/risk management and EIA (-8.0)
- Project structuring, project/risk management and EIA → Project financing (-28.0)
- Project structuring, project/risk management and EIA → Business development (-24.0)
- Project structuring, project/risk management and EIA → Reduction of CapEx and OpEx (-18.0)
- Project structuring, project/risk management and EIA → Technology learning (-14.0)
- Project structuring, project/risk management and EIA → Consenting, leasing, licensing (-10.0)
- Project financing → Business development (-2.0)
- Project financing → Reduction of CapEx and OpEx (-2.0)
- Project financing → Technology learning (-2.0)
- Project financing → Consenting, leasing, licensing (-2.0)
- Business development → Reduction of CapEx and OpEx (-6.0)
- Business development → Technology learning (-6.0)
- Business development → Consenting, leasing, licensing (-6.0)
- Reduction of CapEx and OpEx → Technology learning (-13.0)
- Reduction of CapEx and OpEx → Consenting, leasing, licensing (-11.0)
- Technology learning → Consenting, leasing, licensing (-11.0)
- Consenting, leasing, licensing → Undeared decommissioning (-22.0)

**Fig. 9: SD-model 3: Negative impact on the development of marine energy**



### 7.2.7 Insight matrix and ranking of top-level driving factors

To retain the x-axis designation as for SD-model 1 (Fig. 6) and SD-model 2 (Fig. 8), the results of SD-model 3 (countervailing) are shown on the left-hand side in Fig. 10 (reference is made to Appendix E.3.2).



**Fig. 10: SD-model 3: Insight matrix**

In Table 21, the item numbering in the insight matrix is explained (see “#”) and the top-level driving factors identified by SD-model 3 “Negative impact on the development of marine energy” are numerically ranked.

**Table 21: SD-model 3: Ranking of top-level driving factors**

	<b>Ranking</b>
Technology learning (#25)	83
Marine operations experience (#15)	74
Project structuring, project / risk management and EIA (#21)	61
Consenting, leasing, licensing (#5)	51
Business development (#3)	46
Device operation experience (#7)	36
Funding requirement (#10)	24
Project management (#20)	19

Identical to SD-model 2, the strongest (negative) impact on the development of marine energy is given by “technology learning” (defined as per the identical calibration in SD-models 2 and 3 now with an impact level of 83) and “marine operations experience” (74). As both are identically identified as being decisive by the reinforcing as well as by the countervailing model, the close-to-reality modelling and practical applicability of the computed results is underlined.

### **7.3 Calculated allotment of primary interview statements**

Based on the questions listed in paragraph 8.2.2, in the following interview statements focussing on aspects with negative impact onto the development of the sector are summarised.

#### **7.3.1 Technology learning (#25)**

Marine energy is considered as technically challenging. It was stated that the technology is not properly developed and not fully proven. An initial naïvety in the sector and over-optimistic developers created unrealistic targets. Frustration was generated in the investment community because promised TRLs could not be met.

Some interviewees criticised the diversity of technologies and outlined that too many different concepts are under development. According to them, excessive focus was put on incremental technology and not on a staged development. An intensified concentration on multi-applicable technologies and joint concepts is recommended.

In recent years, technology barriers were not addressed adequately and it needs to be realised that there are “no short-cuts” in the development process. The lack of collaboration in the industry is seen as critical.

#### **7.3.2 Marine operations experience (#15)**

A general underestimation of marine challenges was communicated. The sea is a harsh environment and it is much harder to deploy there than expected. To prepare for this complicated work, access to appropriate testing facilities is required. It was emphasised that no demonstration device has yet operated with a high level of availability for more than three years. Early life faults need to be engineered out of commercial products prior to deployment.

#### **7.3.3 Project structuring, project / risk management and EIA (#21)**

Apart from safety aspects, keeping project budgets and schedules is considered as key.

#### **7.3.4 Consenting, leasing, licensing (#5)**

A lack of motivation due to the global financial crises and missing government leadership (in some countries) was detected. Apart from difficulties with keeping consultation deadlines, high cost and an uncertainty in permitting were mentioned.

### **7.3.5 Business development (#3)**

Struggling to engage other sectors like oil & gas was mentioned as a major problem. It is required to bring in such knowledge and thus to achieve a consolidation of skills. The limited involvement of large OEMs (at the time of the interviews) was criticised. Furthermore it was lamented that the industry presented itself as being at a more advanced state of development than it really was which led external stakeholders (e.g. policy-makers and funding bodies) to direct their resources towards tackling barriers other than the one the industry immediately faced.

### **7.3.6 Device operation experience (#7)**

The uncertainty in device performance and reliability derives from a lack of focus in proving the technology. A key requirement is to minimise the lack of experience and to prove the concept's merits.

### **7.3.7 Funding requirement (#10)**

The uncertainty about the economic payback of projects and limited knowledge about the life expectancy of devices held back rapid development. It was stated that the development of the technology is much more expensive than expected. The necessary funding to cover project costs is far greater than initially anticipated in the earlier formative years of the sector.

Previously, investment came from grant funding and angel investment. Now that investment is being made from large engineering companies, quicker progress is being made.

Due to the difficulty in getting investment, early commercial pressure hindered cooperation. Understandably, the development of the sector would have been quicker if more money would have been available, as outlined by one interviewee. With increasing costs and limited resource for acquiring the necessary investment, developers had to move at a slower pace. Funding drove the engineering.

As a global statement, an interviewee referred to the relatively low level of support for the marine energy development compared to e.g. nuclear energy, where it was in the range of £3 billion.

### **7.3.8 Project management (#20)**

In this paragraph, the negative impacts on the development of marine energy due to partly questionable project management performance are listed separately for the different project phases:

- Disadvantageous decisions made during the initiation and concept phase can create significant negative impact on the project outcome. The limited availability of data complicates decision-making.
- In the course of the planning and design phase, the decision on selecting the right technology is decisive.
- Cost overruns in the manufacturing and testing phase create negative impact.
- Limited accessibility and restricted weather windows can substantially complicate erection and commissioning.
- The commercial operation phase can be negatively impacted by high O&M costs and low energy yield values.
- The required efforts for decommissioning can be easily underestimated.

Regarding risk transfer and risk propagation processes, the most significant negative impact on the development of the sector was related to the often unclear contractual responsibility for the achievable energy yield. This was due to several step changes concerning the quality of information and the risk ownership.

## 7.4 Chapter summary

The following conclusions are drawn from the chapter:

- An initial naïvety in the sector and over-optimistic developers created unrealistic targets. This led external stakeholders to direct their resources towards tackling barriers other than the ones the industry immediately faced.
- The industry presented itself as being at a more advanced state of development than it really was. Frustration was generated in the investment community because the technology readiness levels were not as promised in some cases.
- The development of the technology is much more expensive than expected. The necessary funding to cover project costs is far greater than initially anticipated.
- The uncertainty about the economic payback of projects and limited knowledge about the life expectancy of devices holds back rapid development.
- The reason for the lack of collaboration in the sector is caused by early commercial pressure.
- The uncertainty in device performance and reliability derives from a lack of focus in proving the technology.
- The responsibility for the achievable energy yield is transferred several times between the study phase and the start of commercial operation. To limit the negative impact, a continuous overwrite of risk ownership is required.

So far in this thesis the emphasis has been on defining milestones and on extracting knowledge about positive and negative impact factors on the development of the sector. In the following chapter(s), this information will be effectively integrated in order to define and develop a series of prioritised strategy options. To fully substantiate the findings and to motivate stakeholders to transpose some of the recommendations into their action plans, precisely matching expert statements and current literature quotations are presented to complete the picture.

Demonstrating a continuously high level of transparency in the process of strategy-finding is a prerequisite for achieving the envisaged high credibility of the results.

## **8 PRIORITISED STRATEGY OPTIONS**

The difficulties hindering the market breakthrough of marine energy are manifold. In the literature review, the main challenges the sector faces are highlighted and investor restraint is made evident. Although ideas for advancing the sector and improving the investment climate are dealt with by literature, the presentation of a conclusive set of measures to effectively advance the commercialisation of marine energy is missing. Well-founded arguments and coordinated strategies to work stepwise towards market acceptance are required to mitigate the hindering circular relationship between unquestioned device reliability and achieving funding. Stakeholder-wide balanced strategies to de-risk pilot deployments are necessary in order to create investor confidence and to reach generation cost competitiveness on the long term.

### **8.1 Stakeholder-specific measures to close the gap in literature**

The target behind the elaborated methodological approach is to transparently analyse data obtained from expert stakeholders in order to create practical implications to successfully direct the marine energy development trajectory. The approach is comparable to the one of Richards, Noble and Belcher (2012) on the use of bulk data collected by semi-structured interviews for multidimensional analytic research on technological, economic, social and public barriers to renewable energy development.

Following the results of the system dynamics model 2 and 3 calculation runs, the most important reinforcing and countervailing factors for the development of the marine energy sector are listed in Table 22. In contrary to the strategy options described in the later chapters 9 and 10 on the aspects of pre-competitive collaboration and the nature of complexity that apply to all stakeholder groups, the recommendations in this chapter are intended for being reflected in stakeholder strategy or action plans. Impact factors of similar nature are grouped into the principal domains as “technology-driving stakeholders”, “policy framework”, “financing sector” and “business development and strategy planning”. The individual impact levels are given in parenthesis.

As the insight matrix axes scales in both system dynamics models are identically parametrised by the software tool (Figures 8 and 10), the top-level driving factor

rankings in Tables 19 and 21 can be directly compared in magnitude<sup>27</sup>. Although there is no direct coupling between the two SD-models, the relative proportion of impact levels between the two top-level driving factors “technology learning” and “marine operations experience” confirms this calibration<sup>28</sup>.

**Table 22: SD-models 2 and 3: Combined ranking of top-level driving factors**

Counter-vailing	Principal domains and top-level driving factors	Re-inforcing
<b>Technology-driving stakeholders (551)</b>		
83	Technology learning (#25 & #35 = 183)	100
74	Marine operations experience (#15 & #19 = 160)	86
61	Project structuring, project/risk management & EIA (#21 & #29 = 105)	44
36	Device operation experience (#7 & #7 = 63)	27
-	Marine technology (#20 = 21)	21
19	Project management (#20 = 19)	-
<b>Policy framework (100)</b>		
51	Consenting, leasing, licensing (#5 & #5 = 100)	49
<b>Financing sector (59)</b>		
-	Reduction of CapEx and OpEx (#30 = 35)	35
24	Funding requirement (#10 = 24)	-
<b>Business development and strategy planning (123)</b>		
46	Business development (#3 & #4 = 123)	77

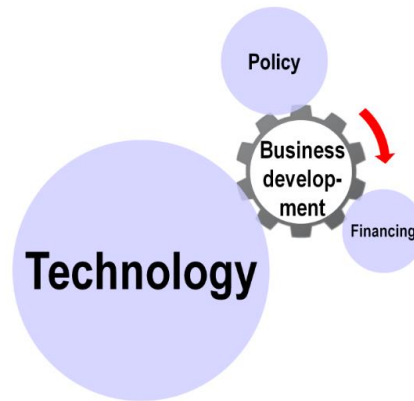
The elaborated stakeholder-specific strategy options are based on different knowledge sources, i.e. primary interview replies, social science literature and original research triggered by the knowledge on the ranking of top-level driving factors. To ensure the traceability and credibility of the arguments, in the detailed paragraphs backward references are made to the expert interview part and to the primary results generated in the course of the system dynamics modelling process.

The dominance of technology-related aspects (with a summative impact value of 551) is obvious and explainable by the decisive task to reach full technical maturity. The relevance of business development and strategy planning as the interlinking element between technology, policy and financing is underlined by the second highest combined impact level value of 123. This domain drives the management of the

<sup>27</sup> The background hereto is that theoretically it would be possible that the results in one model are per category more relevant than the ones in the other. The principal comparability of the impact levels of SD-models 2 and 3 is given because the quality and relevance of the underlying questions in Appendix B.2 (for SD-model 2 questions #2.1, #2.2, #2.3, #2.4, #3.2.2, #4.1, #4.2, #4.3, #4.4 and for SD-model 3 questions #3.1.2, #3.1.4, #6.1, #6.2, #6.3) is equal.

<sup>28</sup> The percentage difference between these two driving factors is minor with is 14% (ratio 100/86 for SD-model 2), respectively 11% (ratio 83/74 for SD-model 3).

diverse technological challenges under consideration of financial constraints and within the given political framework. The principal domains are displayed in scale according to their impact level proportions in Fig. 11. The image visually underlines the dominance of technology-related issues and the central role of business development and strategy planning.



**Fig. 11: True-to-scale impact on marine energy development**

Representative interview statements allocated according to the combined ranking of top-level driving factors are listed in Table 22. To ensure the full transparency of the presented strategy-finding process, the respective generic terms under which the quoted interview replies were achieved are listed in Appendix D.

- The statements of the technology-driving stakeholders are based on replies under the generic terms “technology learning”, “marine operations experience”, “project structuring”, “project / risk management and EIA”, “device operation experience”, “marine technology” and “project management” as listed in Table 22 and 23.
- The interview replies relating to the policy framework can be found under “consenting, leasing, licensing”.
- The statements concerning the financing sector were received under the generic terms “reduction of CapEx and OpEx” and “funding requirement”.
- For business development and strategy planning, reference is made to the replies received under the generic term “business development” used in both SD-models.

The interview-based statements and recommendations for sector-specific orientation provide the keywords and basis for the formulation of the prioritised strategy options.



**Table 23: Foundations for sector-specific prioritised strategy options**

<b>Technology-driving stakeholders</b>
<p>Adopt systems engineering principles inspired by the space-/aircraft industry</p> <p>Designing out complexity and failure points</p> <p>Consider that extreme engineering is required with a focus on survivability and reliability</p> <p>Design for installation and maintenance purposes</p> <p>Develop multi-applicable technologies (standardisation of components) and joint concepts</p> <p>Foster third party certification</p> <p>Reduce the number of technological concepts (technology convergence process)</p> <p>Minimise the lack of collaboration and improve knowledge sharing</p> <p>Consider the need to restructure and commit to the supply chain</p> <p>Gain offshore deployment experience with full-scale devices</p> <p>Move from device testing towards array-scale activities under open sea conditions</p> <p>Integrate risk management into project management</p>
<b>Policy framework</b>
<p>Facilitate consenting, leasing, licensing</p> <p>Promote cross-interaction between renewables</p> <p>Support technologies with declared synergies towards offshore wind</p> <p>Encourage initiatives to bring in expertise from offshore oil &amp; gas marine operations</p> <p>Support grid-connected test facilities and pilot zones</p> <p>Strengthen collaboration and alignment between industry, utilities, academia and developers</p> <p>Recognise that pilot projects with availability records provide confidence in core technology</p> <p>Support strategies for grid operation with significant wave and tidal power in-feed</p> <p>Simplify access to the international (out of Europe) market</p> <p>Keep in mind that realism is required when it comes to the (global) scale of the industry</p>
<b>Financing sector</b>
<p>Consider the likelihood of early-stage failures and the failing in unexpected parts of project</p> <p>Focus on cost of electricity and not on capital expenditure</p> <p>Consider that the cost of electricity production is dependent on the capacity deployed</p> <p>Evaluate the insurability of projects</p> <p>Recognise differences to offshore oil &amp; gas with regard to design, manufacturing, logistics</p> <p>Realise the advantage of working with the already existing companies in the market</p> <p>Encourage contract structuring and contract standardisation as in onshore wind</p>
<b>Business development and strategy planning</b>
<p>Note that early market entry can be critical</p> <p>Focus on the integration of the supply chain (building a new industry)</p> <p>Publish industry performance and cost targets</p> <p>Focus on availability of qualified personnel and heavy marine services</p> <p>Stimulate appropriate risk sharing between the stakeholders</p> <p>Recognise the importance of knowledge sharing (central bottleneck)</p> <p>Struggle to engage other sectors and bring in skills from the oil &amp; gas sector</p> <p>Respect the natural limitations to rate the growth</p> <p>Avoid selling projects for which the technology is not ready</p> <p>Focus on array-scale design and think about options for short-term energy storage</p> <p>Consider that industry programmes have shorter timeframes than academia</p> <p>Focus on volume production and improvements in engineering</p> <p>Work for strategic transmission infrastructure investment</p> <p>Work on closer collaboration between OEMs and project developers</p>

## **8.2 Technology-driving stakeholders**

### **8.2.1 Apply systems engineering principles**

The interview participants identified concerns about the technological reliability as the top-ranked non-commercial risk and difficulties in achieving funding as the key commercial risk. The widespread perception of high cost and unproven technology was identified as negatively influencing the development of the marine energy sector. Reasons why the sector has not developed more rapidly were repeatedly correlated to the uncertainty of device or system performance.

According to a Scottish government employee, the failure of devices was the most fundamental and greatest single reason for projects being delayed or costs increased. Representatives from a UK financial firm and a Canadian project developer confirmed that project delays and cost overruns mainly relate to the performance of the energy converters. The urgency to demonstrate equipment reliability at utility-scale was underlined by a machinery expert. The programme director of a leading centre of sustainable energy expertise outlined that it is necessary to provide transparency to investors and to focus on “bringing some 10 MWs in the water”. By doing this, the viability of electricity generation by marine energy will be demonstrated as a whole.

When asking for significant potential to get the cost for utility-scale project implementation down, the emphasis of a converter firm representative was on orientating the development and research strategies at the US space-/aircraft industry and here in particular on the systems engineering principle. To achieve satisfactory technology reliability records, further experts recommended focussing on reliability in system design and on the introduction of reliability modelling. As an example of lessons learnt in the offshore oil & gas industry being transferred to marine energy, a senior manager at a Canadian utility mentioned their strict focus on reliability and survivability.

In the course of the design and deployment of multi-device arrays, regular system functionality checks, targeting the final goal of grid-connected operation were recommended. The importance of considering maintenance and repair strategies in the design phase was emphasised by the representative of a device manufacturer. The

relevance of transmission infrastructure investments and support strategies for grid operation with significant renewable in-feed is underlined.

According to the opinion of a utility's marine energy project manager, one of the top-priority tasks for the work of academia and research should be to concentrate on multi-applicable technologies and system components (e.g. moving parts, cable connectors, interfaces). To ensure identical component delivery, effective supply chain management and leveraging logistics are required. For the theoretical background, reference is made to the benefits by simulation-based supply chain collaboration as described by Elkady, Moizer and Liu (2014).

### **8.2.2 Foster technology convergence**

In the course of the interviews, a utility's representative underlined the expectation that technology convergence will get the cost for commercial-scale project implementations down. By this process and the further industrialisation of the sector, productivity will be improved and thus significant economies of scale achieved. The intention is to achieve that marine energy converters are considered as reliable end-products based on a standard design (e.g. three rotor blades in wind power).

When being asked about the most valuable experience gained by the "early movers", a project developer's head of offshore mentioned the "negative impact by missing standardisation". Considering the urgent need for consensus over standardisation, an offshore test site manager referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). The project manager for a wave power plant summed up the situation by saying "no standards, no results".

It needs to be taken into account that regular commercial projects will be realised under institutional financing by competitive bidding. To enable standardised project performance assessments, third-party certification of array-scale installations is required. This means that an independent classification society confirms the compliance with legal-normative standards and contractual obligations, as a minimum.

The European Marine Energy Centre (EMEC, 2009a; EMEC, 2009b; EMEC, 2009c) lists two kinds of certification:

- Type certification refers to a marine energy converter built in serial production or to parts of it. It consists of an assessment of the compliance with contractual requirements in the production, manufacturing, deployment and commissioning phases as well as during operation (see also DNV, 2008 and Bittencourt Ferreira and Zarraonandia, 2015).
- Within a project certification, it is assessed whether the site conditions (e.g. meteorological and oceanographic data, soil properties, environmental aspects and powergrid data) conform to those defined in the terms of reference or contract document. The project certificate refers to design, manufacturing, installation and commissioning, including grid connection.

In the context of proving the “array-scale success”, a comprehensive integrity assessment of the technological concept is required. This includes both type and project certification.

### **8.2.3 Strengthen knowledge sharing and collaboration**

The limited sharing of knowledge in industry and between project developers is seen by the strategy manager of a public-private partnership and by the head of energy of UK’s innovation agency as one main reason why the marine energy sector has not developed more rapidly. A senior policy officer emphasised the need to transfer lessons learnt in the offshore wind industry in order to avoid duplication of time and effort. The project manager for the implementation of the world’s first commercial breakwater wave power plant underlined the need to improve the sharing of (bad) experience and testing data. To support progress, the interviewee suggested that it would be valuable to explain at conferences why things went wrong and to describe the finally implemented solution.

Senior members of classification societies stressed the uncertainty about reliability as a major risk factor and emphasised the need to focus on it. The development manager of a wave energy converter firm explained that their company approach towards risk management is to cooperate with a multi-national oil & gas exploration corporation.

He stressed the requirement to share risks by collaboration and to integrate risk management into project management. A law firm's contract expert highlighted that risk sharing should be contractually optimised in order to identify the most appropriate risk-owners. Apart from the need for contract standardisation and collaborative contracts, he recommended contract splitting as practised in offshore wind. An owner's representative mentioned that engineering consultancies should share risks with project developers<sup>29</sup>. In order to follow the new definition of risk as described in paragraph 2.4.3 and to precisely steer the "effect of uncertainty on objectives" (ISO, 2009), a compliant marine energy risk management plan needs to directly focus onto the final target of achieving full-commercial power generation. The close and strategic management of risk complexes that may affect the project performance either positively or negatively needs to be a central task from the pre-feasibility stage to decommissioning.

In order to efficiently achieve strategic goals in innovative projects, it is necessary to share knowledge and to establish a cooperative working environment. Intensified collaboration and improved knowledge interchange between device and project developers is of prime importance because it can serve as orientation for the renewable energy policy-makers. Furthermore, concepts are required to mitigate the entrepreneurial tendency to compete in very early stages instead of forming coalitions and alliances.

### **8.3 Policy framework**

In the 2012 edition of the World Energy Outlook (IEA, 2012a), it is described that fossil fuels remain dominant in the global energy mix for years to come. They are supported by subsidies that amounted to US\$523 billion in 2011, which is six times more than the subsidies to renewables, according to IER (2010) figures. The consequential long-term average global temperature increase by the unaltered use of carbon-based energy sources is given at 3.6°C. According to a report of the EU Climate Change Expert Group (EU, 2008), a global mean temperature increase greater than

---

<sup>29</sup> It shall be noted that this might be a critical issue, as the contract values for consulting engineering firms are usually much too low as to assume project execution risks.

2.0°C will result in increasingly costly adaptation measures and unacceptably high risk of large-scale irreversible effects. The legally binding UK Climate Change Act (Department of Energy & Climate Change, 2008) was established to ensure that the net UK carbon account for the year 2050 is at least 80% lower than in 1990.

Especially for the UK, low-carbon electricity generation by tidal current and wave power schemes is a promising option for the age of renewables as the marine resources around the coastline are significant. Pessimistic and optimistic assumptions show a technically exploitable resource of 16 to 38 TWh per year (Carbon Trust, 2011), which is significant compared to the UK total electricity consumption of 357 TWh in 2012 (IEA, 2012b).

Referencing to the experienced technological learning in offshore wind energy, Smit, Junginger and Smits (2007) suggest national and international policy-makers design long-term policies for adequately dealing with immature and emerging power generation technologies, such as marine energy. It is generally recognised that grid-connected test facilities and pilot zones are of high value to prepare the move from device testing towards array-scale activities under open sea conditions. Subsequent pilot projects with availability records will provide confidence in the performance of the core technologies and thus improve the investment climate.

As identified by the basic SD-model 1, decisive for the successful commercialisation of marine energy is the strong and long-term commitment from government. The diametrical opposite – fluctuating or unclear political support – creates a similar level of (negative) impact. The research of Corsatea (2014) concludes identically by formulating that policy variations induce new risks on marine energy finance.

Oriented along the top-level driving factors identified by the SD-models 2 and 3, the following policy-related representative interview statements were received:

- A main concern is the need to facilitate consenting, leasing and licensing, e.g. by establishing a single point of handling. Furthermore, the regular adaptation of public support programmes and incentive mechanisms to actual developments is seen as crucial to push the development and to accelerate progress. Potential conflicts of interest (fishery, offshore wind, military, shipping routes, tourism) need to be addressed in early project stages.

- In the course of promoting cross-interaction between renewables, focus should be put on supporting marine energy technologies or components with declared synergies towards offshore wind. Initiatives to encourage bringing in expertise from offshore oil & gas operations need to be fostered. Intensifying collaboration and sharing of knowledge by improving the alignment between academia, device manufacturers, project developers and utilities are of key relevance.
- Considering large-scale deployment, the importance of strategic transmission infrastructure investments and options for short-term energy storage cannot be overestimated. Support strategies for grid operation with significant wave and tidal in-feed are required and existing capacity bottlenecks need to be resolved.
- Some interviewees underlined the importance of simplified access to the international (out of Europe) markets. Nevertheless, it was observed that realism is required when it comes to the global scale of the industry.

Uba (2010) outlines that a broad participation of stakeholders and extensive reliance on expert advice are seen as preconditions for a legitimate and successfully implemented renewable energy policy.

Airbus is a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments (European Ocean Energy Association, 2013).

## **8.4 Financing sector**

The two major risks for multi-megawatt projects, identified as concerns about reliability and difficulties in achieving funding, form the key bottlenecks to the development of marine energy. The qualitative assessment driven by SD-model 1 supports these findings and reveals that the lack of investor confidence can be resolved by demonstrating the “array-scale success”.

As LCOE was identified to be more relevant in the long term than capital expenditures, guideline procedures are required to identify the techno-economic optimum way for harvesting marine energy. The importance to consider that the cost of power

production is dependent on the capacity deployed was emphasised (see also Bucher and Couch, 2013).

Considering the statement of a project developer's representative towards the need to compromise cost and reliability, the insurability of the projects must be kept in mind in any case.

By continued industrial R&D, in combination with offshore site testing, the project implementation risk is reduced. The direct consequences are steadily accumulating sectorial development cost caused by: (i) the ongoing effort to achieve technology maturation; (ii) further extended credit commitments; and (iii) loss of profit due to non-realised commercial projects. The time pressure to implement marine energy projects is amplified by continuously decreasing subsidised feed-in tariffs because of the expected progress in concept maturation and steadily declining generation cost in competing renewables such as wind and solar.

In the course of marine energy project developments, it is necessary to accept that extreme engineering is required. In the financial scheme the likelihood of test or early-stage failures needs to be considered. The differences to offshore oil & gas with regard to the level of investment, design characteristics and required logistics are fundamental.

In the course of the interviews, the advantage of working with existing companies and apply collaborative contracts was outlined.

## **8.5 Business development and strategy planning**

Business development and strategy planning usually focus on identifying new and innovative business segments and aim at implementing growth opportunities within and between stakeholders. The respective departments and organisations deal with medium- and long-term planning and thus subliminally direct the future orientation of the public and private bodies. In marine energy, business development fulfils the function of a "flexible coupling element" between the technology-driving stakeholders, policy-makers and the financing sector.

The interview replies received under this domain mainly relate to (i) the consistency in policy-making and lobbying; (ii) bankability and transparency to investors; (iii)



long-term development of the sector and strategic partnerships; (iv) knowledge sharing and collaboration; and (v) transmission infrastructure upgrading.

Business development and strategy planning must always remain up-to-date and its directives require regular adjustment to ensure efficient stakeholder interaction and pro-active solution finding. Without a common stakeholder-wide goal orientation, i.e. by jointly working towards the marine energy market breakthrough, individual stakeholders might be tempted to primarily orientate their business development and strategic planning to self-serving requirements. Barlow (2000) generalises that common objectives of several project parties are more important than individual ones.

The management task to develop a market entry strategy for an innovative generation alternative such as marine energy also comprises the execution of activities in the field of public relations. The lack of major marine energy industry success stories and attempts to sell projects for which the technology was not ready, as formulated by the interviewees, generated temporary setbacks that now need to be compensated. In order to advance the sector, benefits are seen in publishing substantiated industry performance projections and realistic electricity generation cost targets.

Knowledge management and inter-firm collaboration represent major constituents of the commercialisation strategy. Limited knowledge sharing is recognised as a central bottleneck, which can be removed by closer cooperation, e.g. between OEMs and project developers. Further profit is seen in bringing in skills from the oil & gas sector. When combining industrial and university research, it needs to be considered that industry programmes usually have shorter timeframes than academia. In this context, Cassiman, Di Guardo and Valentini (2009) point out that universities and industrial firms have complementary resources and skills: While universities and research centres have access to intellectual resources and a basic research infrastructure, industrial firms can provide practical expertise, financial resources and employment opportunities.

At present, most large industrial players focus on array-scale design and plan for volume manufacturing. Attention must be given to the availability of qualified personnel and heavy marine services at the time needed.

The benefit of harmonising diverging perspectives arises when considering the need to reduce the number of technological concepts, to use synergies between competitors and to transfer existing knowledge. A key challenge is to support the exchange of information and good practice between the competing stakeholders.

A presumed cornering of the market by early movers was criticised in the course of the interviews. This will not be a strategy for the future.

Negotiating risk allocation and appropriate risk sharing between the stakeholders is relevant for realising cost-efficient projects. Unrealistic risk allocation creates additional cost and can lead to project cancellations. As an example, Westwood (2005) reported that two major offshore wind projects were delayed because bidders were not prepared to accept the foreseen EPC contracts and the consequential risk ownership. Risk allocation is particularly important because it can strongly influence the commitment of the project parties and the quality of how uncertainty is managed. Without a clearly defined risk distribution, either party is likely to try to manage uncertainty primarily for their own benefit, mostly to the disadvantage of others and the project.

According to Al-Reshaid (2005) projects often proceed to execution with insufficiently well-defined specifications. The arguments outlined on fundamental uncertainties in complex projects are specifically relevant for marine energy projects due to their innovative character. This concern is supported by Atkinson et al. (2006) who outline that conventional project management does not pay enough attention to the conception and end phases as well as to strategic aspects of projects.

In the course of the performed interviews, a classification society's representative underlined the general importance of standardisation and certification. He emphasised the need to accelerate the development of robust and reliable marine energy technology solutions and recommended to carefully balance progress with a level of risk acceptable to all involved stakeholders.

## 8.6 Chapter summary

The following conclusions are drawn from the chapter:

- The main task of the technology-driving stakeholders is to improve the device reliability. A number of innovative concepts are presented to resolve that issue.
- Within the policy framework, the global CO<sub>2</sub> reduction targets are dominantly defining the development trajectory towards renewable generation. For marine energy, strong and long-term commitment from government is decisive.
- To gain investor confidence, it is necessary to pass the interim milestone “array-scale success”. After this proof of maturation, the financing sector will be in the position to foster large-scale deployment.
- Business development and strategy planning play a key role in fostering the information flow between the technology-driving stakeholders, the policy-makers and the financing sector. As the respective departments and organisations deal with medium- and long-term planning, they play a key role in the strategic orientation of the sector.

The unbiased processing of multi-level expert interview data by system dynamics computer modelling allows the identification of prioritised strategy options ready to be transposed into stakeholder-specific action plans.

Apart from the application of the outlined strategy options, the successful market introduction of marine energy requires the management of manifold organisational and technical aspects, of which the following two were chosen for further in-depth examination:

- As reducing the identified lack of cooperation and improving knowledge sharing are key contributors for progress in the sector, it is required to identify how to create motivation to implement corresponding measures.
- Considering the demanding challenges that need to be overcome, an analytical assessment of the nature and characteristics of diverse problem complexes is necessary in order to get into the position to apply adequate solution paths.

## 9 FROM COLLABORATION TO COMPETITION

The reason to investigate on the concept of collaboration and competition was triggered by the result ranking of the top-level driving factors “technology learning” and “marine operations experience”. In the underlying interview statements, the “limited knowledge sharing in industry” was criticised and the need to “intensify cooperation between developers” as well as to “share lessons learned between projects” was emphasised. Regarding the status quo of marine energy from a technology development perspective, it shall be noted that even without the system dynamics computing result ranking, the conclusion to investigate upon pre-competitive collaboration could have been reached based on the primary interview data and the literature review.

When developing measures to accelerate progress by advancing the technological maturity in the marine energy context, a differentiation between collaborative stakeholder interaction and competitive concept selection processes is required. In line with the differing characteristics, a split is made between the phases of technology development and project implementation:

- **Technology developers**  
The motivation for enterprises to enter into collaborative interaction is examined. The arguments that substantiate the application of pre-competitive collaboration, consider the need for a multi-company-based market breakthrough. Joint benefits by intensifying the sharing of knowledge and expertise between competitors are described. It is explored how pre-competitive collaboration and inter-firm alliances can positively influence the success rate of commercialising marine energy.
- **Project developers**  
The characteristics of competition-driven technology selection processes in the course of implementation projects are investigated.

In both cases, reference is given to sectors in which comparable methods are successfully applied.

## 9.1 Signs of an immature technology

Apart from public support regimes to help commercialise marine energy, strategic partnerships between utilities and device manufacturers are currently in place. By jointly financing and managing pilot projects, the transition from single-device testing towards array-scale deployment is streamlined and the correlated risks are shared.

Current examples of such direct partnerships are:

- ScottishPower Renewables has received consent to construct and operate the 10 MW Sound of Islay demonstration tidal array electricity generating station. The ten 1.0 MW candidate devices are supplied by Andritz. Installation was planned to start in 2016 (Marine Scotland, 2015).<sup>30</sup>
- ENGIE informed that four Alstom 1.4 MW tidal turbines will be installed at a pilot project in the Alderney Race in France. Deployment of the first device was scheduled to begin in 2018 (GDF SUEZ, 2014; ENGIE, 2016).<sup>31</sup>

It is noteworthy that in the global power sector such bilaterally agreed contracts would not be in line with principal regulations for projects realised under the rules of ICB. The probability of getting best-available technology at a market-balanced price would appear to be critically reduced. However, due to the limited manufacturer spectrum in the marine energy sector, such arrangements seem to be without alternative for the present transition period.

Regular commercial marine energy projects will be realised by institutional financing and under consideration of standard procurement principles. Herefore, a number of equally competent manufacturing firms is required to be in the market at the time of the market-rollout to ensure realistic pricing and to avoid single-bidder dependency. It is necessary to create and maintain a broad supplier spectrum enabling a sustainable market participation.

---

<sup>30</sup> Atlantis purchased the Sound of Islay site from Scottish Power Renewables in 2016. The project has full consent and an agreement for lease from the Crown Estate. Atlantis intends to build out the site in 2018 (Tethys, 2018).

<sup>31</sup> Even it does not impact the drawn conclusion, it shall be noted that ENGIE recently suspended the project as GE (that took over Alstom) decided to stop the development of the Océade tidal turbine (Le Parisien, 2017).

## **9.2 Technology developers: Effective collaboration**

### **9.2.1 Automotive industry reference cases**

Almost ninety million cars and commercial vehicles were manufactured worldwide in 2014 out of which 0.23% were equipped with electric drive. Due to the dominance of fossil-fuel combustion engines and the massive global oil infrastructure, the market introduction of electric cars has the character of a radical or even disruptive innovation, which is characterised by causing a dramatic market change. As from a development trajectory perspective, the starting positions of marine energy is comparable considering the outstanding market breakthrough, the collaborative strategies applied by the industrial conglomerates in the car sector are examined more closely:

- The electric car manufacturer Tesla is treating its patents as open source and informs that “it’s not the other companies that are our competition, but the combustion engine itself”. Tesla has set the goal of populating the world with battery stations to fuel the future of electric cars. An interesting viewpoint of the company is that “patents are meant to slow competition but they also slow innovation” (Tesla, 2014). In similar manner, Toyota decided to give away fuel cell patents to encourage other automakers to enter their concept and to boost as such the industry (Toyota, 2015).
- BMW and Daimler agreed on a cooperation with the strategic goal of achieving the wholesale market-rollout of electric cars by working on a common infrastructure for inductive battery charging (Proff, 2013). The concept was implemented in the Daimler 2016 test fleet.
- Ford, Nissan and Daimler have signed a hydrogen fuel cell development agreement in an effort to bring affordable vehicles to market by 2017. The companies, which have so far been working on the technology separately, plan to jointly develop a common electric vehicle system. As such, a clear signal is sent to suppliers, policy-makers and industry to encourage the further development of hydrogen refuelling stations and other infrastructure necessary to allow the vehicles to go to mass market (Daimler, 2013).

Although the scale of production of the global car industry is not comparable to the relatively small marine energy sector, in the highly innovative field of alternative drives, comparable obstacles and questions prevail. Both sectors, e-mobility and marine energy, deal with radical innovations that imply non-linearity and discontinuity with the potential to change practice and markets. The explicit strategic target of Tesla to supersede the combustion engine finally requires, similar as for marine energy, a multi-company market breakthrough. This includes the setting up of a charging infrastructure correlated with the reinforcement of existing power networks and the installation of new energy storage facilities or other flexibility options to buffer demand peaks.

At this point, a principal similarity to marine energy becomes obvious: In both cases, fluctuations in power generation (intermittency of tides and stochastics of waves) and consumption (charging of e-cars) strongly affect the operational concept of the existing power infrastructure. Grid stabilisation measures are necessary in areas with a high density of e-car charging stations (in high traffic or urban areas) and at remote coastal sites to connect marine energy arrays. Significant investment in distribution grid upgrades and the transmission lines to coastal areas will be required.

Similar as for the e-car sector, public investment into the embedding infrastructure will be required for marine energy (Jeffrey, Jay and Winskel, 2013). Regarding the product lifecycle, a perspective of ten years might be reasonable for both sectors.

### **9.2.2 Strategic alliances**

In conventional power projects, usually fully proven (or gradually updated) technology with extensive reliability records is implemented. In contrast, marine energy pilot arrays will be equipped in key parts with prototype-design technology. Reliability is an important factor of success for all emerging technologies. The proof of reliability remains a major challenge, as most devices to date have been in the water only for short periods compared to the expected service life.

In the course of the expert interviews, a fundamental difficulty in sharing knowledge and experience between the marine energy stakeholders was mentioned. Triggered by the system dynamics modelling results, the necessity to strengthen inter-firm cooperation and to form alliances was clearly identified. In a situation where industrial

competitors accept the high significance of jointly achieving the market breakthrough (i.e. the “array-scale success”), the motivation for implementing (temporary) inter-firm alliances increases.

Magagna and Uihlein (2015) outline that despite attracting wider interest and more investments than the tidal energy sector, wave energy technologies have not reached the same level of reliability and technological readiness of their tidal counterparts. As there is at present more market confidence in tidal current than in wave power (Wyatt, 2014), the form and intensity of inter-firm cooperation might differ.

Consequently, in the following both sectors are considered separately as per the:

- Potential scale of deployment and trends

The scale of deployment according to figures about the global extractable capacity for both technologies is in the range of 100 GW as described in the literature section. The potential associated with wave energy worldwide is estimated to be 29,500 TWh/yr (World Energy Council, 2016). The tidal current potential is estimated between 800 and 1,100 TWh/yr (IEA/OECD, 2007). In both sectors, first array projects have been or are under implementation. The most prominent example in tidal current is MeyGen and in the wave sector, it was the world’s first multiple machine deployment of three Pelamis<sup>32</sup> P1 devices at the northwest coast of Portugal in the year 2008.

Wave energy devices can be placed in three distinct categories: point absorbers (e.g. Wave Star), attenuators (e.g. Pelamis) and terminators (e.g. Wave Dragon). Rusu and Onea (2017) show that today most of the research activities focus on projects that involve point absorber systems. The authors conclude that the near future of the wave power industry will most likely be related to the implementation of hybrid (i.e. wind/wave) projects. This finding underlines the importance of collaborative approaches.

Regarding the tidal energy development, Neill et al. (2017) remind that at least six first generation seabed-mounted tidal turbines have completed testing at EMEC and that same type machines are presently installed at MeyGen and Nova

---

<sup>32</sup> The company went into administration in November 2014 and the device is no longer being developed.



Innovation. Second generation tidal turbine designs show two notable areas of evolution as they are of floating designs and sold as components to be integrated by others. The unit capacity rating ranges now from 100 kW to 2 MW whereas most first generation machines were rated at 1 MW.

- Potential market size

The global wave and tidal energy market has been valued at US\$498 million in 2014 (Transparency Market Research, 2016). Estimating the individual future market size is highly speculative and not predictable as the market rollout is outstanding.

- Scope and manufacturing details

In tidal current, cooperation might focus on non-turbine parts (foundations and moorings, balance of plant), the requirements of the surrounding infrastructure (cable connector systems, grid and control interfaces, port facilities), aspects of operation (device / array interaction, offshore inventions) and resource characterisation. In Zhou (2017) information on large fixed and floating tidal turbines is provided. As these megawatt-devices represent the industrial solutions for several pre-commercial farm projects, it is noteworthy that the fixed-type units are all of horizontal axis design and nearly half adopt fixed-pitch blades.

In wave power, a consistent technology assessment framework is required by which less credible technologies can be screened out. The attractiveness of exploring the prospects by co-locating wave and wind power devices was emphasised by the interviewees.

Above examples on realised technology convergence options improve the potential for inter-firm cooperation. Larsson et al. (1998) identified that an inter-firm relationship is reinforced by the degree to which the competitive objectives diverge between the partners.

Brink (2017) outlines for the offshore wind sector in a qualitative case study, different types of innovation collaboration between small and medium size enterprises:

- Demand-driven

In this case, the need for supplier cooperation is based on contractual requirements (performance guarantees, risk sharing) formulated by investors or implementation agencies. The companies are forced to find alliance partners who can provide the funding to work on the larger contracts. The focus of the short-term cooperation is on price and components to be delivered. In case successful for both parties, the engagement can end in a partner-driven collaboration.

- Supplier-driven

This type of cooperation can emerge among suppliers working repeatedly on the same customer project. The companies can join forces to be a “one stop supplier” solution for the larger enterprise and hereby provide a more attractive and cost effective solution to the larger enterprise.

- Partner-driven

This approach focuses on persistent collaboration between equal partners that are interested in joining efforts to develop the sector and to reduce the cost of electricity. Strong and long-term commitments are required between the partners.

Considering the explained case studies and findings, the planning and implementation of pre-competitive collaboration between manufacturing firms requires a precise context analysis and a clear target orientation to successfully support the companies and finally the sector. At the present stage of the marine energy sector, the demand-driven concept is the most realistic one.

### **9.2.3 Pre-competitive collaboration**

Reducing the lack of collaboration and improving knowledge sharing is key for advancing the sector. A sustainable technology breakthrough needs to be based on a number of equally competent manufacturing firms to avoid non-competitive market structures. Single-bidder dependency is not acceptable for large-scale projects. It is expected that the sharing of engineering knowledge and environmental data supports continuous design improvements and fosters the technology convergence process. A

higher level of cooperation between technology developers minimises the risk for replication and duplication in manufacturing.

At the present stage of development, a joint focus on achieving the marine energy market breakthrough is required (Bucher and Jeffrey, 2015). Apart from the consideration that marine energy represents a radical innovation, a few closest-to-market full-scale prototypes require moderate improvement by incremental innovation as described by Jeffrey, Jay and Winskel (2013).

As concluded by Alkemade, Kleinschmidt and Hekkert (2007), governments play a crucial role in creating initial niche markets, because they hold the power to change legislation and can articulate demand for new technologies by acting as early users or by formulating policy targets. Talke (2005) underlines the importance of carefully planned and consistently implemented market entry strategies for products with high grades of novelty. Within the marine energy context, Corsatea (2014) identified that coordinated interaction between technology developers and policy-makers endorses market formation. The correlated shift to a new socio-technical system includes the creation of a new market.

To fulfil two main requirements, i.e. (i) to achieve the market breakthrough; and (ii) to create a new market, extraordinary concessions between natural competitors are required. Joint efforts can focus on common infrastructure for deploying, operating and maintaining devices (harmonised technical interfaces) as well as on reducing the level of patent protection. These circumstances were explained previously for the structurally comparable market introduction of electric cars based on decisions by major industrials like Tesla, Toyota, Daimler and BMW.

Radical novelties can only break through after growing in a protected environment and under the support of subsequent strategic investments. With the goal to develop the marine energy technology to the level of reliability required to survive in the power market, so-called “incubation rooms” (offshore test facilities) were created. It is expected that collaborative behaviour, which is at present particularly relevant in test field environments, will finally pay-off by profiting from a new market segment.

Pre-competitive collaboration as an established concept has been successfully applied in various industrial sectors.

### **9.3 Project developers: Competitive concept selection**

#### **9.3.1 Hydropower and offshore wind reference cases**

Different forms of competitive technology qualification routines or concept selection processes have been applied in large-scale hydro and offshore wind:

- The 70 MW Waldeck I extension hydroelectric pumped storage plant: During the planning phase, three construction/engineering consortia were invited to submit binding offers for design and construction concepts comprising all civil and electro-mechanical works. The most advantageous fixed-price plant concept, elaborated at moderate cost for the employer, was awarded for implementation. The other participants were compensated for their engineering effort. The project risk could be considerably reduced at an early stage finally leading to a successfully completion of the construction and start of commercial operation (Tenders Worldwide, 2010).
- The Alpha Ventus wind farm: Twelve 5 MW turbines were implemented 45 km offshore in waters 30 m deep using an innovative approach. Two types of turbines were built on two different types of foundations (tripods or jackets). The experience gained by different designs and the combination of concepts provided valuable information regarding efficiency and reliability which is crucial for future offshore project realisations (Alpha Ventus, 2011).

Although different with regard to technological aspects and the amount of investment, above project examples have one aspect in common: in both cases, a widespread research and manufacturer spectrum became accessible leading to the systematic identification of suitable solutions for implementation. The approach provides a solid basis for the further marine energy development or larger project implementations.

#### **9.3.2 Marine energy reference cases**

Several project competitions have been launched to advance and de-risk the sector. In the following, two examples are provided: One focussing on the staged implementation of a large-scale tidal array and the second on a government-funded initiative to accelerate the development of wave energy technology.

- MeyGen Limited was granted in 2014 a marine licence for the Inner Sound project in the Pentland Firth (Marine Scotland, 2014). The project comprises the deployment of up to 398 MW of tidal current turbines by the early 2020s. The Scottish government has provided £23 million of funding to help develop the tidal stream farm, which started to export electricity in November 2016 (MeyGen, 2014). A “deploy and monitor strategy” was announced by MeyGen (2016). In this initial two years pre-project phase, a demonstration array of up to 6 turbines with two different turbine suppliers (Atlantis and Andritz) and the required on- and offshore balance of plant systems will be implemented. The equipment design and integration will be tested in the target environment as “a precursor to the subsequent development of the remaining lease area”. The experience from the construction, installation, operation and maintenance will be used for the final project. MeyGen emphasises that the project design is flexible enough to accommodate other equipment supplier designs if needed. They explain that one of the key reasons for this phased approach is that before the final deployment on such a large commercial array can begin, the installation and operation of the technology must be proven beforehand on a smaller scale. The MeyGen approach, publically communicated in 2016, complies in its principles with the competitive technology qualification routine developed in the course of this research.
- Wave Energy Scotland is a technology development body set up by the Scottish Government to facilitate the development of wave energy. It manages a number of competitive project calls, funding the development of strategic areas. A key objective is to avoid duplication in funding, to encourage collaboration between companies and research institutes and to foster greater standardisation across the industry (Wave Energy Scotland, 2014). The experience is being shared to avoid others having to go through the same learning exercise. Some projects focus on combining the strengths of several key promising technologies to adaptively achieve the best trade-off. Wave Energy Scotland has initiated a project with the European Marine Energy Centre<sup>33</sup> to capture the knowledge and experience

---

<sup>33</sup> EMEC was established in 2003 to test wave and tidal energy converters in real sea conditions and has hosted to date 16 wave and tidal energy clients from nine countries with 25 marine energy devices.

amassed through testing of wave energy devices in real sea conditions. 4 out of 8 technology developers were awarded a total of £2.8 million after successfully competing to join an innovation programme (Wave Energy Scotland, 2017). The project teams can apply for funding to develop a scaled prototype device for real sea testing at EMEC. The organisation commissioned a consortium of 7 companies (QinetiQ Ltd, Black & Veatch Ltd, Ricardo UK Ltd, DNV GL, Energy Technologies Institute, Carnegie Wave Energy, Offshore Renewable Energy Catapult) to investigate the opportunities for technology transfer from more mature technology sectors into the wave sector (Catapult, 2016). The challenge was to identify opportunities for the novel application of technologies, knowledge and practices from industries outside of marine energy and to examine those that could be deployed to fast-track the development. As part of improving the coordination between private and public sector investors, a potential role for government in underwriting debt finance for the industry is described. Wave Energy Scotland applies a competitive technology development process to bring forward projects that promote greater confidence in the technical performance of wave energy systems. The organisation emphasises, that this calls for rigorous assessment of wave converter designs and difficult decisions about investment.

Both examples represent transparent and fact-based selection approaches to reliably identify the most suitable technology solution for a specific application or marine site. They increase the predictability of the technical and economic performance of a conceptual idea or an underlying commercial-scale project. Reference is made to paragraph 2.2.3 and Bucher (2012) in Appendix F.2.

### **9.3.3 Fast-track concept assessment**

Based on the result ranking by the system dynamics model 1, Tables 12 and 13 list tasks in the context of “collaboration and consolidation between companies”. They are directed towards minimising the “low ability of developers to work together”, eliminating “fragmented initiatives by unexperienced parties”, preventing “failed demonstrations / technology failures” and avoiding “critical events regarding H&S<sup>34</sup>

---

<sup>34</sup> Health and safety

(negative press)”. The total of these factors creates nearly two-thirds of the impact onto the goal of achieving the interim milestone “array-scale success”. The output by the system dynamics models 2 and 3 (Tables 19, 21 and 22) reveals that “technology learning” and “marine operations experience” have the strongest impact on the strategic target of achieving market competitive electricity generation. Both have the potential to minimise the “lack of experience of developers”, to reduce the “limited knowledge sharing in industry”, to intensify “cooperation between developers” and to share “lessons learned between projects” as per representative replies formulated by the interviewees (Appendix D). The mentioned need for “better sharing of engineering and environmental data” and “collaborative research” directly target creating inter-firm alliances and implementing the concept of competitive collaboration.

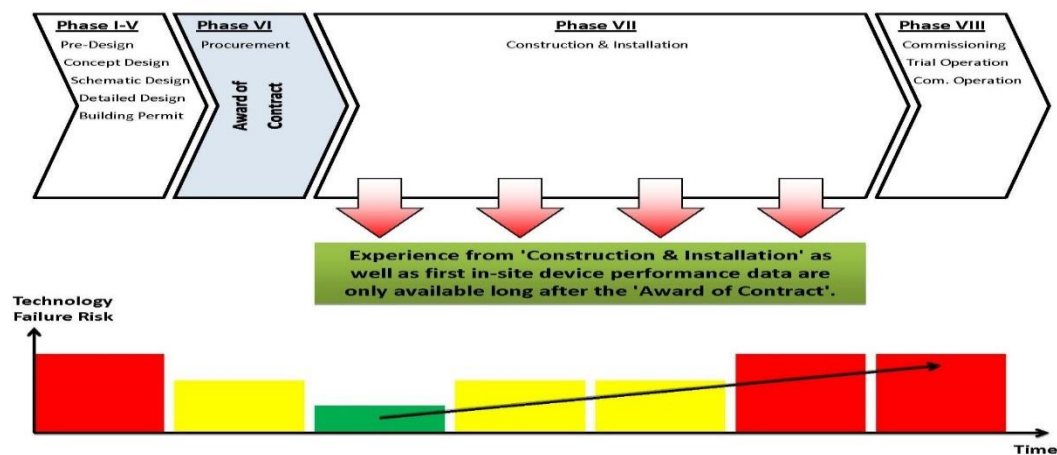
Marine energy needs to assert its position in the highly competitive power market. The envisaged market introduction can be seen as a unique opportunity taking into account the ongoing difficult funding situation and the incalculable consequences of negative events in the course of implementing pilot installations. To make full use of this one-off chance, intense and trustful collaboration is required. Marine energy must avoid going to market without fully developed components or a questionable long-term system performance. The current systemic problems need to be targeted in a coherent manner with a high-level of coordinated strategies and precise action plans.

#### **9.3.4 Competitive technology qualification routine**

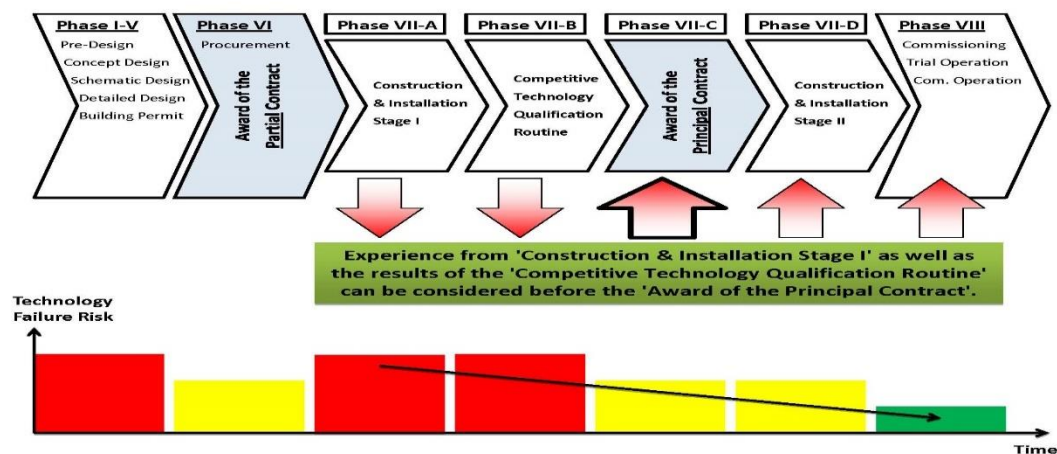
As the pressure to commercialise marine energy is high, a reliable approach to identify best-performing equipment is required. At the time of starting the research, no such concept was described in the literature or executed in the marine energy context. In the course of the research, a novel concept selection or technology qualification routine was developed by which project implementation risks can be considerably reduced (Fig. 12 and 13). The proposed routine enables access to the full supplier market spectrum and allows bringing in comprehensive manufacturer competence by which challenging projects can be reliably developed in order to finally operate economically.

To accelerate and finalise the technology maturation process, a concept to integrate R&D into commercial-scale projects is presented. The effect of the naturally slow technology development and concept evolution process can be mitigated by creating a

functional concept based on market-driven mechanisms. The principal idea is to establish a contractual framework by which various sets of marine power conversion devices can be installed and operated under real conditions in the final site for a limited period within an initial stage of a commercial project. The overall device performance is assessed and the best-ranked device is selected for full-scale implementation. Non-successful participants in the competition are adequately compensated to cover their accumulated design, engineering, manufacture, installation and maintenance costs. Amending projects with a competitive technology qualification routine increases the safety of investment. As an interim solution until full maturity is reached, the concept fulfils the function of an incubation room required for bringing novelties to market.



**Fig. 12. Conventional power project phasing**



**Fig. 13. Optimised power project phasing**

For details, reference is made to the literature review section 2.2 Demonstration projects and pilot installations, as well as to Appendices F.2 and F.3.



## 9.4 Chapter summary

The following conclusions are drawn from the chapter:

- As commercial marine energy projects will be realised by institutional financing, a number of equally competent manufacturing firms is required to be in the market to ensure realistic pricing and to avoid single-bidder dependency. Where industrial competitors accept the high significance of jointly achieving the market breakthrough (i.e. the “array-scale success”), the motivation for collaboration will increase.
- With the prospect of making profit in a new market and the potential to implement utility-scale projects on regular basis, a strong motivation for effective interaction in the industry aiming to jointly de-risking the technology is given. The required efforts for putting corresponding measures into practice can be justified by the expected profits after the market breakthrough.
- The (temporary) joining of forces in the form of pre-competitive collaboration is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence. Extraordinary concessions between “natural competitors” are required. Pre-competitive collaboration between technology developers enables to minimise replication and duplication in manufacturing.
- The principle of amending a project implementation with a “competitive technology qualification routine” can be applied to improve the overall project performance and to increase the safety of investment. Within the marine energy context, it is of special interest to investors, project developers and manufacturing firms. Marine energy must not go to market without fully developed components or a questionable long-term system performance.
- Advancing high-risk phases to earlier project stages limits the overall project risk.
- Cooperation between developers supports continuous design improvements and fosters the technology convergence process. The number of technological concepts can be reduced and the use of multi-applicable technologies and standardised components intensified.

## **10 DYNAMICALLY COMPLEX OR “JUST” COMPLICATED?**

Complexity research differentiates between detail and dynamic complexity, which is relevant for identifying effective strategies. It is decisive to accept this primary classification, as measures appropriately applied on one type of complexity can be counterproductive if applied on the other. In order to identify an optimum strategy before making a decision, an apparently complex problem needs to be analysed and split into the different categories of complexity.

### **10.1 Background**

The main obstacles to the maturation and commercialisation of marine energy are problems with device reliability and difficulties in attracting investment. To ensure continuous progress on the way towards subsidy-free electricity generation, the application of diverse problem-solving methods is necessary. On one side, there are technical and organisational difficulties that require profound engineering expertise and outstanding administrative capabilities and on the other, intertwined tasks of a strategic nature for which qualitative assessment capabilities and advanced strategy-finding skills are necessary (Bucher and Bryden, 2014a).

Various interviewees emphasised that device design shall not primarily focus on operation performance but on simplified installation and maintenance. The need for designing out complexity and failure points as well as applying concepts of modularity and redundancy was emphasised repeatedly.

It is expected that technology convergence and continuous design improvements result from the ongoing efforts to reduce the likelihood of early-stage failures.

For further details, reference is made to section 2.6.

### **10.2 Reduction of detail complexity**

In the context of marine energy, questions of detail complexity arise in the framework of machinery design (e.g. foundations, blades, rotor, nacelle, electrical, control and protection systems) and partly in subjects related to deployment, operation and retrieval or in multi-faceted organisational tasks (legal permits, regulatory and consenting process, finance applications).

For detail-complex problems, the application of complexity-reducing measures is expedient, as underlined by Groesser (2011a) in a power plant engineering context.

### **10.3 Managing dynamic complexity**

The process of commercialising marine energy comprises a high grade of dynamic complexity, caused among others by the continuously varying interaction between many heterogeneous stakeholders and the embedding socio-technical environment.

When looking onto the development history of the sector, the impact by dynamic complexity becomes apparent when analysing the root causes for the experienced setbacks and delays. One example for this is the circular correlation between the need to improve the device reliability and to achieve funding. This correlation is affected by the dynamically developing socio-technical environment and a certain policy resistance, as technology development processes need time and can only be accelerated to a certain level.

In Table 24 (adapted from Sterman, 2001; Geels, 2004; Groesser, 2012), typical attributes of dynamic complexity and archetypical causes of their appearance are listed. In the right-hand column, marine energy specific root causes and their case-specific effects on the sectorial commercialisation are explained. The table serves to create a better understanding of the relevance of time-related and multi-dimensional problems slowing down the development of the marine energy sectors.

For dynamically complex problems, the application of feedback-oriented methods, e.g. in the form of interviewing experts from the full range of stakeholders is appropriate. Within this thesis, the transparently performed elaboration of prioritised strategy options can be seen as the result of a qualitative feedback (modelling) process.

On the long term, creative solution finding strategies, taking into consideration the theoretical background regarding the basic difference between detail and dynamically complex problems are required.

**Table 24: Dynamic complexity: Typical attributes and the marine energy case**

Typical attribute	The marine energy case
<p><b>On-going transformations in the embedding socio-technical system</b></p> <p>Innovation and change processes occur at many levels and at different time scales.</p>	<p><b>Root cause:</b> The unstable global economic situation constitutes a dynamic environment and changing strategic priorities (climate change, nuclear power phase-out, fracking) alter policy orientation.</p> <p><b>Effect:</b> Considering a business environment in which other renewables are cost-competitive to non-renewable sources and the epochal transformations the global energy system is undergoing, the marine energy commercialisation strategy needs to be regularly adapted to socio-technical developments.</p>
<p><b>Non-linear development and unsteady system behaviour</b></p> <p>Non-linearity arises when:</p> <ul style="list-style-type: none"> <li>(i) multiple factors interact, i.e. by complicated information pathways with many decision points;</li> <li>(ii) cause and effect are distant in time and space; and</li> <li>(iii) effect is rarely proportional to cause.</li> </ul>	<p><b>Root cause:</b> Leete, Xu and Wheeler (2013) and Wyatt (2014) examined investor attitudes and found that most are unlikely to make future investments in early-stage device development. Venture capital investors are not closed to the industry completely, but the current level of risk and uncertainty about future revenues discourages them from investing.</p> <p><b>Effect:</b> The commitment of investors is key for continuous progress and the successful commercialisation of marine energy. The present uncertainty of costs and the length of time required to develop the technologies limit the incentive to invest and contribute to the unsteady and non-linear progress in the sector.</p>
<p><b>Counter-intuitive effects and policy resistance</b></p> <p>The complexity of a system can make it difficult to fully understand it. The attention is often drawn to symptoms rather than to the underlying causes of problems. Many seemingly obvious solutions to problems fail or even worsen the situation.</p>	<p><b>Root cause:</b> The limited predictability of advancement in the sector is illustrated by the unexpected decision of Siemens to sell Marine Current Turbines (a key tidal current device developer) only two years after its acquisition in 2012. Siemens exit marine energy, saying the development of the market and the supply chain has taken longer to grow than expected (Siemens, 2014).</p> <p><b>Effect:</b> The decision of Siemens to divest of MCT was a concern for the sector (IEA-OES, 2014a). It revealed the difficulty of forecasting the pace of development for reaching commercial generation even by an industrial conglomerate. The 2013 decision of Voith Hydro to shut down its wave power business Wavegen (acquired in 2005) reflects the background situation.</p>
<p><b>Adaptive characteristics</b></p> <p>Evolution and learning lead to the selection and proliferation of the best concept(s) while others become extinct. Achieving a milestone alters the state of the system, thus giving rise to a new situation, which then influences the next decisions.</p>	<p><b>Root cause:</b> Marine energy represents a radical innovation and needs to de-risk the technology to achieve funding. Before becoming recognised as a mature generation method, it needs to prove a range of referenceable application cases. The attainment of this “array-scale success” represents a major turning point and is expected to trigger industry-scale deployment.</p> <p><b>Effect:</b> The economic success of marine energy depends on demonstrating market-readiness. By the game-changing “array-scale success”, competition between suppliers will shift to a new set of parameters of which the most important one is price (Teece, 1986). The development trajectory adapts.</p>
<p><b>Tight inter-coupling</b></p> <p>Heterogeneous stakeholders interact intensively with one another and the natural world.</p>	<p><b>Root cause:</b> Interaction of diverge stakeholder groups such as governments, certifiers, investors, academia, consultancies, developers, owners, operators, manufacturers, test site operators.</p> <p><b>Effect:</b> To successfully realise the marine energy market launch, closely and regularly coordinated interaction of the policy, technology and finance sectors is necessary.</p>

## 10.4 Root cause compliant strategy measures

To apply the knowledge about dealing with complexity, the identified impact factors (Table 12), top-level driving factors (Table 22) and prioritised strategy options (Table 23) are analysed in terms of their suitability for supporting complexity reduction and for improving the management of dynamically complex tasks, or for a combination thereof.

Detail-complex tasks are defined by their complicacy and dynamically complex tasks by their challenging time and feedback behaviour. A great number of tasks comprise a mixture of both elements. The following task classification as per the two constituents of complexity serves to create a better understanding of which measures best to apply to which type of problem or situation.

- The strategy recommendations focussing on reducing detail complexity mainly relate to technology development. When taking into account the need for extreme engineering and the focus on reliability and survivability, the dimension of the engineering challenge and technology barriers becomes apparent. In order to work towards gaining a satisfactory technology reliability record, failed demonstrations need to be analysed and corresponding machinery design targets re-adjusted.

The development of multi-applicable technologies and joint concepts helps to reduce the number of concepts and fosters the technology convergence process. As the identified marine energy target focus is on array-scale design, technologies with declared synergies towards offshore wind become the focus. Further aspects with a high level of detail and the need for precise interaction relate to the development of international standards and the harmonisation of contracts as in offshore wind.

- Managing dynamic complexity is more challenging and requires direct access to distributed knowledge and multi-level strategic information. By nature, policy-makers and financing experts focus on such long-term development and consciously not on detail or routine tasks. As business developers and strategy planners try to avoid being blocked by daily problems and detail challenges, their view is comprehensive and long-term oriented.

The intention by demonstrating commercial-scale projects is to confirm the technical reliability and to reduce the lack of investor confidence, i.e. to resolve the circular (dynamic) correlation between the two top-ranked risks “reliability” and “achieving funding”.

For efficiently fostering technology learning, it is necessary to overcome the low ability of developers to work together and to improve knowledge sharing – both aspects that require to deal with long-term and counter-intuitive interests.

Questionnaire-based semi-structured expert interviews provide a reliable basis to create fundamental knowledge required to manage the outlined tasks.

- A number of strategy recommendations target detail and dynamic complexity. The presented competitive technology qualification routine is a good example acting on both types. On one hand, detailed technical problems can be detected during the trial operation period and on the other, strategically relevant market insight and operational experience is gained. In order to “design out” complexity (as formulated by an interviewee), it is recommended to adopt systems engineering principles inspired by the space-/aircraft industry.

A further example, to which both aspects of complexity apply is the need to identify a cost-effective way to harvest marine energy and to reduce CapEx and OpEx.

To successfully establish marine energy as a mature generation alternative, decisive issues need to be assessed in their entirety and root-cause-oriented solution approaches applied. The systematic differentiation between detail and dynamic complexity supports long-term effective case-specific strategy-finding.

## 10.5 Chapter summary

The following conclusions are drawn from the chapter:

- To successfully establish marine energy as a mature power generation alternative, in-depth engineering capabilities and advanced strategy finding concepts are needed. The stakeholders need to foster diverse problem-solving competences: one for complicated technology-related or organisational tasks and another for managing non-transparent strategic remits.
- Detail complexity (or complicity) is characterised by many interdependent elements and a large number of combinatorial possibilities. The application of complexity-reducing measures is expedient.
- Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships with accumulation or delay functions and the need to integrate hard and soft data. Aspects of dynamic complexity require long-term observation and the application of cautious intervention measures. Feedback-oriented methods for strategy-finding provide best results.
- Relevant tasks need to be assessed in their entirety and corresponding root-cause-oriented solution approaches applied. In order to identify an optimum strategy before making a decision, an apparent problem complex needs to be analysed in its entirety and systematically categorised as per being detail or dynamically complex or a combination thereof.

As the outcome of the empirical research and the theoretical study is now comprehensively explained, the discussion of the findings and the formulation of the conclusions form the next and final steps.

## 11 DISCUSSION AND LIMITATIONS

The main function of this chapter is to answer the research questions in the light of the achieved findings and results. The scientific significance, the implication of the findings and the contribution to knowledge are described in view of the understanding of the problem before and after having conducted this research. It is outlined how the identified gap in literature has been filled and how the answers fit into existing knowledge on the topic elaborated in parallel to this work. Furthermore, the limitations of the methodology are described. Structured along the research questions, the major findings are interpreted and put into context with regard to their level of novelty and scientific impact.

### 11.1 Major findings by addressing the research questions

As formulated in the literature review chapter, the marine energy sector finds itself in a decisive transition phase having developed full-scale demonstrators but lacking proof of the concept in a commercial environment. After the decades-long development process with larger than expected setbacks and delays, investors are discouraged because of high capital requirements and the uncertainty of future revenues. Even the primary literature makes investor restraint evident and provides ideas for advancing the sector, a conclusive set of stakeholder-specific measures to manage the market breakthrough was not available when starting this research.

#### 11.1.1 Pivotal milestones and prioritised strategy options

The first part of the first research question “*What are the pivotal milestones for commercialising marine energy?*” targets on basically orienting the marine energy development trajectory.

The data input for the corresponding first system dynamics model was generated by analysing the replies to the interview question on the top-level impact factors for reaching commercial generation. The underlying causal diagram was built one-on-one to the qualitative replies, so that it directly reflects the experience and expectation of the stakeholders. The supporting and hindering arguments were interlinked and used to constitute the structure and content of the model.



In order to make best use of the available momentum in the sector, the research targeted the identification of interim and long-term milestones in order to recommend strategies that enable an efficient continuation and termination of the maturation and commercialising process.

By sorting the ranked impact factors, the consecutive milestones were defined as:

**(i) Government support**

Consistent and clear government policies are key for the marine energy industry and the sector in its present stage. Government support is the foundation for progress towards reaching market competitiveness. Apart from stable revenue support mechanisms, strategic investment in learning spaces that allows the innovative technology to develop a development trajectory for reaching maturity is necessary.

**(ii) Array-scale success**

The market breakthrough and thus the proof of the commercial viability depends on a utility-scale demonstration project, i.e. the “array-scale success“. The statistical ranking of the major risk complexes for multi-megawatt projects is led by “achieving funding” and “device reliability“. Both are directly interlinked because funding is required for improving device performance and vice-versa. To pass the singular hurdle of getting market acceptance and to create investor confidence, stakeholders need to (temporary) join forces between competitors.

**(iii) Cost reduction**

Once the maturity and market competitiveness of power generation by marine energy technologies are proven, the development trajectory will adapt and the strategic focus will move towards cost reduction.

Focus was put on the context around achieving the “array-scale success“, as the attainment of this interim milestone represents a turning point for the marine energy business. Once the maturity of the concept is proven, the financing of large-scale installations by international development banks or institutional investors will be simplified. Reaching bankability will finally trigger large-scale deployment.

The second part of the first research question “*What are the prioritised strategy options for commercialising marine energy?*” targets the development of stakeholder-specific strategies to de-risk pilot deployments and to work in a systematic manner towards achieving the market breakthrough. Driven by the outcome of the literature review, a conclusive set of measures to fundamentally support the maturation and commercialisation of the marine energy sector was elaborated. The underlying expert interview information is allocated according to the calculated ranking of combined top-level driving factors.

The synthesis of interview data is suitable to be transposed into individual business and action plans and is presented in stakeholder-specific manner:

**(i) Technology-driving stakeholders**

Apart from financing and regulatory aspects, the key challenge to pass the singular hurdle of getting market acceptance is with the technology providers. The limited sharing of knowledge in industry and between project developers is a major reason why the marine energy sector has not developed more rapidly. Especially for this stakeholder group, at the present stage, it is vital to minimise competition and to strengthen collaboration. This must happen on the organisational side in form of improved knowledge sharing as well as on the technological side by applying systemic concepts. The sector will benefit by more open discussions on why things went wrong and what solutions were finally implemented to resolve a problem.

An important element in the design and implementation of complex technological systems is to perform regular system functionality checks. The central objective in systems engineering is to consider the finally envisaged functionality of long-term operation in grid-connected multi-device arrays.

It is expected that in the course of the marine energy technology convergence process, the wide variety of concepts and components that restricts the pace of development will be reduced. Natural elements of the forthcoming convergence process are the achievement of design consensus and the identification of undiscovered low-cost strategies. Ideally, productivity will be improved and significant economies of scale achieved. In case a positive embedding environment will not emerge, the convergence on a dominant design might be prevented.

## **(ii) Policy framework**

As an overarching outcome of the research, it was numerically confirmed that at the present stage of development strong and long-term commitment from government is decisive for the successful completion of the maturation and commercialisation process. The diametrical opposite – fluctuating or unclear political support – generates a similar level of fundamental negative impact. In case there are uncertain signals from government, investors are likely to postpone their engagement. As the time horizon to develop and implement an emerging generation technology is in the range of decades, long-term policy goals have to be established and followed.

Coordinated interaction of public and private actors is seen as a key factor of success for the governance of the technology development process. Political incentive mechanism ideally direct towards fostering collaboration and sharing risks between the stakeholders. A good example is cross-industry cooperation at an international level triggered by European Union RDI&D programmes. Apart from supporting offshore test facilities and pilot zones, the provision of incentives to coordinate grid reinforcement at the proximity of promising marine energy sites is recommended.

Regarding the increasing dynamics and complexities in operating power infrastructures with high renewable infeed, it needs to be taken into account to what extent the contribution by tidal currents can be part of the solution. In contrary to wind, wave and solar, this source has a premium value as it is long-term predictable.

## **(iii) Financing sector**

As concluded in the literature section, high cost associated with marine energy and concerns about the technology readiness level are reasons that limit financial engagement. Most investors show a preference for more mature and proven technologies. To re-establish investor confidence and to multiply institutional engagements, a coherent technology development and market entry strategy is required. As a first step, demonstration projects with transparent availability records can provide insight into the economic viability and the reliability of the equipment and power export systems. To convince investors, it is necessary to successfully achieve an “array-scale success”. After this proof of concept, the decision makers in financing institutions have better arguments to (re-)engage in the marine energy sector.

#### **(iv) Business development and strategy planning**

In each of the defined stakeholder groups, business development and strategy planning teams with a focus on medium- and long-term perspectives are engaged. To orientate the individual business targets in a future-proof manner, the managers have to be in continuous information interchange and discussion with their respective counterparts. Consequently, business development plays a key role in fostering the interaction between technology suppliers, policy-makers and the investment community and as such to drive the strategic planning.

As business development is directly interlinked with stakeholder PR<sup>35</sup>-activities, the publication of transparent status updates and (conservative) projections on achievable interim goals is important. Reported attempts to sell projects for which the technology was not ready generated setbacks and loss in confidence that had to be compensated with high effort.

#### **11.1.2 Determinants for success of large-scale deployment**

The second research question “*What are the determinants for success of large-scale deployment?*” literally focuses on the time after having achieved the market breakthrough.

As the foundation for a sustainably growing marine energy sector is laid in the pre-commercial stage, the determinants for success need to be defined for the different stages. This starts with the market entry phase to the time of expanding the market position up to finally safeguarding the market participation on the long-term.

#### **(i) Market entry**

Before having reached sufficient technological maturity, the sensitive management of the young sector is of decisive relevance. As highlighted in the literature section, the provision of “niches” that act as “incubation rooms” is necessary to temporarily shield marine energy from mainstream market selection. To overcome conventional organisational inertia, learning spaces that allow intensified levels of collaboration and knowledge sharing are required. In the course of the interviews, a lack of collaboration

---

<sup>35</sup> Public relations is the practice of managing the spread of information between individuals, organisations and the public.

in the industry was mentioned and partly explained by the early commercial pressure in the sector. Early-stage failures by inappropriate or even counterproductive action have the potential to set back the sector by years. Potentially, then the available window of opportunity might be closed.

To achieve the market breakthrough and to establish marine energy as a new industrial sector with a variety of competent manufacturing firms, extraordinary concessions between “natural competitors” are required. The (temporary) joining of forces in the form of pre-competitive collaboration before having achieved the market breakthrough is beneficial with regard to passing the singular hurdle of getting market acceptance and creating investor confidence. In some aspects, the intention to motivate industrial competitors (that might have invested several million euros in developing their own technology) to share valuable know-how and hard-earned experience might seem naïve. As it is in the elementary interest of all stakeholders to make best use of the present pre-commercial period, a basis for enforcing trustful interaction might be to more intensively engage in standardisation bodies, industrial associations and lobby groups.

Major power projects are usually realised by institutional financing and under the terms of international competitive bidding to allow fair and healthy competition. Consequently, also in marine energy, a number of equally competent firms will be required at the time of the wholesale market-rollout to ensure realistic pricing and to avoid single-bidder dependency. It is essential to establish a common understanding that the final goal of becoming a viable generation alternative can only be achieved by a multi-company-based market entry strategy. The eligibility of a project for constituting the “array-scale success” will be based on the in-depth assessment of the respective techno-economic soundness.

## **(ii) Expanding the market position**

To establish the envisaged market position, it will be required to continuously reduce project risk levels and to improve profitability. Successful projects will require a balanced and fair risk/opportunity-ratio between the stakeholders.

Until full maturity is reached, this can be achieved by accessing the core competences of manufacturers in the course of a concept selection process, the so-called

“competitive technology qualification routine”. The goal of this evidence-based selection procedure is to identify the most suitable energy converter solution for a specific marine project site. Apart from the chance to get first-hand insight into the level of technical complicity and the correlated requirements of each competing device, a key benefit is that contractors’ project management and trouble-shooting capabilities are part of the performance assessment. Advancing high-risk phases to earlier project stages represents a contribution by which the long-term economic performance of a marine energy asset can be improved. The proof of the practical feasibility of the concept is given by press releases around the 398 MW MeyGen (2016) project in the UK, where it was outlined that the equipment design and integration will be tested in the target environment as a precursor to the subsequent development of the remaining lease area.

Once maturity and commercial viability of power generation by marine energy technologies will be proven, competition will shift to a new set of parameters of which the most important one is price. For being market competitive, the cost of electricity need to be comparable or lower to the one of other renewable sources.

### **(iii) Safeguarding the market position**

For long-term operation in the harsh marine environment, effective maintenance and repair strategies need to be in place. Benefits might be achieved by interlinking marine energy with other on- or offshore energy infrastructure projects. As improving system reliability and increasing generation efficiency will be continuously ongoing tasks, an innovation mechanism capable to systematically integrate new knowledge and technological developments is required.

After the market breakthrough and having established the market position, inter-firm alliances might be interesting for companies with diverging competitive objectives. Even described as suitable to address technological challenges and to advance innovation, potential engagements will require in-depth study of potential advantages and disadvantages.

### **11.1.3 New insight by the systems approach to advance strategy-finding**

The third research question “*Does a systems approach, in combination with the use of multi-level interview data, provide new insight for advancing strategy-finding in marine energy?*” is of overarching nature. Apart from purely assessing the relevance of the results with regard to adjusting the marine energy development trajectory, the innovative nature and adaptive characteristic of the approach is evaluated.

#### **(i) Transparency and traceability**

System dynamics as a computer-aided modelling method extends the conventional systems approach for being used in an engineering problem context. The method ensures high rationality and allows partly automated knowledge consolidation. The model-based numerical calculation results provide compelling arguments and are a good basis for debate as management planning and decision-making become more transparent and substantiated. The processing of multi-level expert interview data by applying system dynamics assures an open-integrative instead of detailed-specialist character of an examination. The approach allows an all-encompassing appraisal by avoiding concentrating in a limiting manner on stakeholder-specific views or interests.

Systems thinking stands for assessing a situation made up of dynamically interacting elements instead of looking at isolated events and their individual causes. The causal diagrams elaborated one-to-one in line with the interview data constitute compressed representations of usually dispersed knowledge, originating from different hierarchical levels and in some cases even from oppositely directed perspectives.

#### **(ii) Adaptability and repeatability of the research**

System dynamics modelling in combination with the use of multi-level interview data enables the integration of cross-category information and even contradictive positions. The iterative calculation routine behind the causal diagrams determines the “centre of gravity” of an examined problem complex, i.e. the key strategic drivers that dominantly act onto the defined target factor.

Based on an existing reference system dynamics model, a subsequent examination process can be standardised and is thus much closer to moving realities. If one time programmed, regular updates and adaptations are feasible without high effort.

### **(iii) Trustworthiness of the results**

Holistically approaching and rationally identifying overarching strategies to succeed in a technology-based innovation environment is seen as a contribution that supports transdisciplinary research<sup>36</sup>. System dynamics modelling is employed to develop causal diagrams representing key interactions based on expert considerations. The calculated results are used to structure subsequent in-depth analyses of critical success factors and to elaborate further required knowledge.

The provided unbiased results represent a key contribution and provide a good basis for debate to substantiate critical management decisions. The promotion of results – in this case in the form of prioritised strategy options to be transposed into concrete action plans – is easier to accomplish when being based on expert interview data and traceable computer modelling processes.

### **(iv) Manageability of dynamic complexity**

Driving technological evolution is a tough and painstaking process. Developing an innovative power generation method up to market readiness requires high managerial sensitivity and wide-ranging adaptation capabilities. Even minor detrimental decisions in the course of fine-tuning an innovation project or working on the sectorial development can lead to significant financial impact and the compulsory termination of an engagement, in case not timely corrected.

Dealing with feedback-driven and circular causalities requires the application of comprehensive situation analytics and superordinate strategic measures. As concluded in the literature section, in conventional management, mainly aspects of detail complexity are considered, but the real leverage lies in understanding dynamic complexity. Most of the available planning tools and analytical methods do not address the management of dynamic complexity, necessary in innovative environments where flexibility and tolerance of vagueness are indispensable.

As confirmed by the sensitivity analysis, the definition of time-correlated parameters between impact factors is decisive for achieving reliable simulation results.

---

<sup>36</sup> Transdisciplinary research crosses the boundaries of two or more disciplines to create a holistic approach. Apart from knowledge of the disciplines involved, skills in moderation, mediation and knowledge transfer are required.



## **11.2 Relation of the findings to similar studies**

The present research topic was defined years before the below-mentioned initiatives started or comparable contributions were published. There was no exchange of information or direct interaction so that the formulation of the results in the present research was finalised independently.

### **11.2.1 The Carbon Trust**

A few months after having fixed the research topic, Carbon Trust (2011) published a strategy paper on accelerating marine energy and the potential for cost reduction. It is emphasised that a clear pathway to make wave and tidal stream technologies competitive with other forms of renewable generation is required. Technology innovation needs to be accelerated and the learning rate improved. A continued focus needs to be on innovation breakthroughs that help to reduce cost by minimising, for example, cases of over-engineering. The paper concludes that industry players need to better engage with each other, but unfortunately no new ideas were provided to motivate them to implement corresponding measures. The present research questions, defined prior to the Carbon Trust publication, were formulated to focus on identifying milestones and advancing strategy-finding to successfully commercialise marine energy. Nevertheless their content can be considered as largely congruent with the requirements suggested by Carbon Trust. In retrospect, the relevance of the thematic area and the reason for conducting the present research were confirmed.

### **11.2.2 SI Ocean**

In the course of the two-years project that started in June 2012, a collaborative approach was taken by involving industry experts, European Commission observers and advisory groups on finance, consenting and infrastructure. The extensive engagement included interviews, panel discussions, webinars and workshops reaching 455 stakeholders within a network of 800+ contacts. In the corresponding report on gaps and barriers to marine energy technologies (SI Ocean, 2013a; SI Ocean, 2013b), the need for a twin-track development strategy was described. This shall comprise: (i) large-scale devices to raise the credibility of the sector and to ensure that deployment capacity targets are met; and (ii) small-scale technologies to allow a rapid expansion and proving of early arrays, thus complementing the approach of learning-by-doing.

## **11.3 Unexpected findings**

### **11.3.1 Particular importance of time dependencies**

The sensitivity analysis performed for the first SD-model confirms the importance of defining the time behaviour between the interconnected generic terms and the final target factor. In case no time impact data is programmed, the impact factor ranking is fully congruent with the statistical distribution of the primary interview replies. In case time dependencies are programmed, the system dynamics simulation has the capability to reflect the situation in marine energy within a dynamic context and thus more realistically. The type of network configuration itself (e.g. the connection of one generic term to one or more group terms) has no impact on the target factor due to the one-to-one factor distribution as the interview data. These findings underline the appropriateness of applying system dynamics tools in strategic management because of the possibility to integrate task-specific time correlations, which are essential when dealing with intertwined issues that are mainly characterised by dynamic complexity.

### **11.3.2 Suppliers neglect common advantage by joint market breakthrough**

As part of the sensitivity analysis, it was explored how the milestone term ranking is impacted when excluding the interview data provided by the 30 device manufactures. Surprisingly, it was found that without the opinion of this stakeholder group, the relevance of the interim milestone array-scale success is slightly decreased. Understandably, from the manufacturers' individual perspective, it might seem preferable to follow internal planning to (first) achieve the market breakthrough. As elaborated in the course of the research, global advantages are seen in putting the market breakthrough on a wider and more solid basis with a number of equally strong manufacturing firms. Single supplier dependency negatively affects the market prospects of marine energy due to consequential investment constraints.

### **11.3.3 Compromising cost and reliability**

A project developer's statement to "compromise cost and reliability" sounds surprising when first heard. In the context, it is important to differentiate between reliability and safety. In order to reduce costly over-engineering, corresponding savings potential and the limits thereof are worth to be investigated.

## **11.4 Interpretation of the results**

As the first part of the interpretation section, the validity of the research method and the achieved results are assessed. It is examined how the understanding of the research problem has changed after the availability of the presented results.

### **11.4.1 Validity**

In most cases in physical science, phenomena can be directly observed or have highly predictable properties. When performing an interdisciplinary research with strong social science components, the proof of the validity of the findings is particularly challenging. As the underlying theory and data might not be strong enough to permit a clear justification of the research method and results, it is necessary to consecutively confirm the coherent and explicit chain of reasoning.

As described in the research design section, highest attention was given to orientate the work along holistic principles to comprehensively identify overarching strategies to target the commercialisation of marine energy. The underlying interview data is provided by carefully selected managers, experts, scientists and specialists from all stakeholder groups. Throughout the research, the high level of transparency was kept by following a systematic information compression process. The prioritised strategy options are determined by system dynamics calculations and are directly substantiated by representative interview statements.

Considering the assumptions and choices made in the design phase of the research, no principal weaknesses were found relating to the theoretical concept (i.e. the construction of theory through the analysis of data) or the modelling approach (i.e. the use of system dynamic principles). Feeding the system dynamics tool with expert interview data has proven its capability to maintain a high level of transparency throughout the process.

A critical point was found in the low number of conducted interviews when considering standard statistical analyses methods. 140 managers, experts, scientists and specialists were contacted, leading to 44 contributions. For the UK and Ireland, the population size was defined at 190 and the sample size at 30 for the respondents from the UK and Ireland. As the focus of the underlying interview series was on accessing high-level expertise from pre-selected experts and not on generating a large

number of mid-level averaged opinions, the application of statistical methods used in phenomenological research is more adequate. According to the respective mathematical formula used by the referenced authors, a sample size of minimum 29 is sufficient. The robustness of the basic system dynamics model and as such the validity of the research results was confirmed by the sensitivity analysis.

In the course of consecutively publishing the core results in scientific journals and regular presentations at international marine energy conferences, the significance and validity of the findings was multiply proven in the course of double-blind peer reviews.

#### **11.4.2 Enhanced understanding of the research problem**

In the course of neutrally analysing the work published by others on the status quo and the prospects of marine energy, a lack of contributions providing strategic guidance to commercialise the sector was identified. While several initiatives have been launched to accelerate the development, no concise methodology was found for unbiased strategy-finding, not even in related fields of innovative and capital-intensive power technologies. The research proposal and the research questions were formulated to fill this gap. In the course of preparing the survey, the status quo of the sector was analysed in detail and a ten-years look into the ideal future was taken to conclude what is necessary to achieve the final target, i.e. full-commercial power generation. To comprehensively address the research problem, a systems-oriented approach to re-adjust the marine energy development trajectory was chosen.

The achieved findings and results improve the understanding of the research problem by providing practically applicable measures for a positive development of the sector:

- As a short-term measure, a concept to resolve the restricting circular relationship between device reliability and achieving funding is provided by identifying the respective top risks and key drivers. As it is unlikely that competing stakeholders will self-reliantly discuss and harmonise their (internal) business strategies, guidance by an adaptive method that is capable to integrate multi-source knowledge and altering priorities is required. The identification and analysis of decisive risk complexes slowing down progress is needed to efficiently prepare the implementation of full-scale commercial projects.

- Regarding the energy environment on the long-term, marine energy can form part of a future sustainable energy mix. It can play a role in the decarbonisation of the power industry and support reaching global carbon reduction commitments. Due to the age of many of the existing conventional generation facilities, a demand for new (and additional) capacity is given. As confirmed by the research, consistency of policy-making and stable framework programmes are key for achieving this goal. Holistically approaching and rationally identifying overarching strategies to succeed in a technology-focussed innovation environment is seen as a significant contribution. The high level of transparency and traceability of the research is made possible by an open but systematic and formalised information management process. In order to sustainably remain competitive in the dynamic energy business, continuous adaptation to ongoing developments and global trends is required.

Due to the continuous transformation of the socio-technical environment, the strategic orientation of the stakeholders needs to be regularly adjusted for which evolutionary steering mechanisms and systemic thinking capabilities are required. The ideal strategy-finding concept must be flexible and re-adjustable to new developments. In line with the closed-loop control concept, a cyclical status imaging process is required for reliable strategy (re-)adjustment.

The persistent difficulties in achieving commercial viability in marine energy are remarkable considering the relevant public support programmes and the significant private investment made over many years. The lack of well-founded strategies and realistically defined targets to systematically work towards achieving the market breakthrough are identified as the key reason behind it. Without high-level coordination and intensified cooperation, resources might be further directed towards tackling perceived barriers other than the ones the industry immediately faces.

When taking into account the presented research results, the understanding of the examined problem complex has positively changed. Relevant forward-looking concepts about mitigating risks and resolving key difficulties the sector faces are made available.

## **11.5 Synthesis of scientific significance and sectorial implications**

### **11.5.1 A new methodological approach to improve strategy-finding**

The key original contribution from the thesis is methodological. It comprises the use of a systematic and transparent methodology for capturing, analysing and interpreting information obtained from expert stakeholders via a structured survey.

The elaborated recommendations for adjusting the marine energy development trajectories are based on an innovative process in which learning and planning are iteratively interlinked. A novel principle applied is to holistically integrate a wide and diverse knowledge spectrum comprising the technology, policy and financing sectors by compiling the information in a fully transparent manner. The approach of processing cross-category expert interview data to create system dynamics causal diagrams constitutes a reliable method to comprehensively analyse the sectorial situation and to identify strategic drivers in an unbiased manner. The stakeholder-specific recommendations for action are suitable to support the commercialisation of marine energy on a fundamental level. The combination of expert interview data and system dynamics modelling allows the identification of reliable and practically relevant strategies.

Regarding the challenges the sector faces, the presented approach is seen as more credible and appropriate than conventional company-internal and directly profit-oriented strategy planning. In this contribution, the inherent high level of transparency and traceability derives from the systematic identification of the top-level driving factors strictly oriented at the content and structure of the underlying multi-level expert interview data. The research confirms that combining the systems approach with a highly formalised information management process leads to new insight and unconventional findings, helping to orientate the marine energy development trajectory. The presented results were achieved by rethinking how to reliably govern politically relevant technology maturation processes.

The presented methodology can be applied in other fields of innovation in which orienting development trajectories is challenging because of the technological novelty of the product and the effects caused by a dynamically changing socio-political environment. Peer-group-based arguments help to address the need for change.

From a theoretical perspective, the maturation and commercialisation of marine energy can be regarded as a complex dynamic system that has to continuously adapt to a changing environment. Consequently, there is a permanent need for strategic adjustment and change management. The elaborated research method allows a regular assessment of the strategic alignment and thus supports the adaptation to a continuously changing and steadily more complex socio-technical system<sup>37</sup>. The systems thinking approach provides the flexibility to comply with these requirements as it is designed to function in non-transparent and dynamic environments. When dealing with time-driven and intertwined impact factors, collaborative concepts and joint problem-solving capabilities are essential.

#### **11.5.2 De-risking the market entry of marine energy**

The defined aim of the research was to analyse the key risk complexes hindering the commercialisation of marine energy and to create strategic knowledge on how to resolve them. Significant constraints were formed by the available window of opportunity and the correlated time pressure to commercialise marine energy. If the first near-commercial array projects do not deliver good returns, the significant investment of the recent years might not be compensated and further investor engagement will be restricted. If pilot installations are not suitable to form good reference cases, the focus of interest might shift to other renewable energy technologies.

The scientific contribution consists in presenting unbiased strategy options that are essential for achieving a broad-based market breakthrough. The systematic strategy-determination process is characterised by a novel level of transparency and traceability which substantiates the findings and puts the arguments for implementing corresponding measures on a convincing basis. While several attempts have been made to elaborate high-level recommendations for commercialising marine energy, the present study is the first to comprehensively address the problems by holistically identifying stakeholder-specific strategy options and action plans.

---

<sup>37</sup> The socio-technical system or regime reflects the interplay of production, diffusion and use of a technology.

The interview-backed arguments and substantiated strategies to overcome the current pre-commercial phase have an implication for the sector, as the available momentum can now be used to efficiently target on jointly achieving the market breakthrough. To resolve the lock-in situation caused by the circular relationship between achieving funding and device reliability – later quoted by MacDougall (2017) from Bucher et al. (2016) as “the financing/technology-demonstration conundrum” – stakeholder-wide coordinated measures need to be applied. This result de-risks the market entry and is of direct practical relevance as no such material was published before this research.

### **11.5.3 Collaboration as a precursor for enabling market competition**

In the course of the interviews, the limited sharing of knowledge and the lack of collaboration were explained by the early commercial pressure in the sector. The intention behind the corresponding part of the research was to improve the understanding that it is in the interest of all marine energy stakeholders to make best use of the presently available window of opportunity and to jointly establish a new industry.

Focus was put on creating an understanding on the joint benefits by implementing the concept of pre-competitive collaboration. With the near-future prospect of realising profits in a new power market segment, there should be a strong motivation for cooperative interaction aiming on jointly achieving market acceptance. The willingness to implement the concept of pre-competitive collaboration will increase when stakeholders become convinced that achieving individual benefits depends on it. The research reminds the stakeholders that the market entry of marine energy is a one-off chance because other forms of renewable energy generation develop in parallel and some have achieved the break-even threshold and are operating successfully in full price-competition to conventional sources (e.g. solar PV).

The scientific contribution consists in providing supportive arguments for intensifying collaboration and establishing inter-firm alliances. A (temporary) joining of forces is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence. The contribution is of interest to organisations focussing on rapidly commercialising marine energy, such as: renewable energy policy-makers, investors, engineering consultancies, project developers and device manufacturers.



Intensified collaboration and improved knowledge interchange between device and project developers is of prime importance because it streamlines project implementation.

Apart from the need to gain experience in the systematic identification and analysis of problem complexes and hindering factors, having immediate access to methods that support the preparation of situation-adapted strategic decisions is essential. It is unlikely that the concerned stakeholders will harmonise their strategy-finding and decision-making without guidance from an adaptive method capable of integrating latest developments and altering priorities. The outlined “competitive technology qualification routine” allows to optimise the lifecycle performance and to increase the safety of investment. This concept is especially interesting for investors, project developers and finally manufacturing firms.

The research results contribute to existing knowledge on how to efficiently achieve the market breakthrough. Based on scholarly literature and experience in comparable industrial sectors, recommendations for the application of appropriate strategies are given. Apart from their applicability in the marine energy sector, the in-depth findings are not sector-specific and can be applied in other innovation-driven contexts. The contribution of the study to practice is to provide prioritised strategy options to be assessed and implemented by the stakeholders’ management.

#### **11.5.4 Application of measures in line with the nature of complexity**

As the development and market introduction of marine energy requires the management of demanding techno-organisational issues, each individual problem complex has to be analysed separately as per its specificity. Based on the theoretical background provided in the literature section, problems can be split into their detail and dynamically complex constituents. Subsequently, different solution approaches apply: one for solving technologically or organisationally complicated tasks (“detail complexity”) and another for the more strategic remits (“dynamic complexity”).

The research reveals that splitting multi-dimensional problems according to the two types of complexity is fundamentally important for allocating effective solution approaches. Working on techno-organisational problems requires fundamentally different capabilities than managing high-level strategic remits. It is important to

realise that measures to reduce complexity are appropriate for solving issues of detail complexity but can be counterproductive in case applied to problems of dynamically complex nature.

Systematically analysing and sub-dividing the tasks to be resolved in the course of commercialising marine energy into questions of detail complexity (i.e. complicacy) and of dynamic complexity represents a novel approach and has an implication for the sector. Reducing the top-ranked risk “reliability” is a challenging but conventional complexity-reducing engineering task, whereas “achieving funding” as the second-ranked risk is more demanding and requires the ability to cope with many interlinked factors at different time scales. It represents a classic example defined by its dynamic characteristic that requires a sensitive and feedback-oriented management approach.

The theoretical concept of sub-dividing tasks of detail and dynamic complexity finds its value when applied to real-world problems in the course of longer-term development and maturation processes.

## **11.6 Limitations of the methodology**

### **11.6.1 Separate consideration of wave and tidal**

The focus of the study was on risk mechanisms for both the wave and tidal sectors. However, as tidal current technology is more close to market maturity than wave, different research priorities might enable more precise and case-specific findings. An area of research for tidal could be on multi-array projects, whereas for wave focusing on tank testing or first pilots might be more appropriate. Nevertheless, covering both technologies under one research approach forces inter-disciplinary abstract thinking.

### **11.6.2 Number of interviewees**

While the quality of data used can be considered as excellent, a few questions of comparably minor relevance could not reach their full potential due to the limited number of received replies. An illustrative example for this is shown in Appendix B.1, which was originally configured to display multiple layers of risk charts for which a larger amount of input data would have been required. Due to practical reasons, a compromise had to be found between data quality and data quantity, whereby emphasis was put on data quality.

### **11.6.3 Sensitivity of system dynamics simulation and robustness of results**

Despite the stability of the first system dynamics model and the reliability of the ranking being confirmed by the sensitivity analysis, it became apparent that the definition of time dependency data between the functional elements is of key importance. Apart from the percentage-wise definition of the impact strength, proportional to the number of interview replies, the time behaviour is decisive for achieving reliable results. The functional correlations between the generic terms, the group terms and the final target is fundamentally related to the programmed time delay parameters.

In case time correlation values are not programmed, the ranking of impact factors will be congruent to the primary statistical distribution of the interview replies. As such, there would be no additional knowledge gain by the modelling and simulation efforts. In order to fully profit from the system dynamics algorithm, it is necessary to precisely define each individual time correlation and thus to generate a unique significance of the results. As part of future surveys, the interviewees might be asked for their estimation of time correlations between factors and delayed impacts as further statistical backup.

### **11.6.4 Minor half-life period for knowledge in innovative sectors**

The system dynamics models generated in the course of this research are based on input by interviews conducted between June 2012 and April 2013. As the marine energy sector is dynamic and innovative, knowledge is quickly superseded or shown to be untrue. Advantageously, the research was oriented along strategic dimensions and, as such, the arguments should be valid for about eight to ten years from the date of the interviews.

A further aspect to be considered is the fact that the global crude oil price has fallen by 50% since the finalisation of the interviews. In between, new forms of hydrocarbon extraction have entered the market (hydraulic fracturing) and solar PV became the cheapest way to generate electricity in many countries. The long-term consequences of these developments and trends on the prospects of marine energy need to be reflected when allocating government subsidies as well as in the course of the stakeholders' strategic planning.

## 12 CONCLUSION AND RECOMMENDATIONS

This final chapter represents a synthesis of key points emerging from the investigation. Recommendations for further research and on how to overcome the limitations of the methodology are given. The research concludes with an outline of final thoughts.

### 12.1 Conclusion

Power generation from ocean waves and tides represents a radical innovation, which is confronted by significant technological and financial challenges. Currently, the marine energy sector finds itself in a decisive transition phase having developed full-scale technology demonstrators but still lacking proof of the concept in a commercial environment. After the decades-long development process with larger than expected setbacks and delays, investors are discouraged because of high capital requirements and the uncertainty of future revenues. The most demanding strategic task is to attract financing and to successfully embed the innovative generation method into the energy infrastructure. The identification of a directed and concise strategy for the market launch in one single attempt is crucial. If stakeholders realise their individual benefit be coordinated action, their willingness to implement them will increase.

In the course of the *literature review*, a lack of well-founded and stakeholder-wide balanced strategies to efficiently overcome the marine energy pre-commercial phase was identified. The identified gap in literature constitutes a key argument for conducting this research in order to precisely determine milestones and to provide substantiated arguments to support stakeholder strategy planning. As over-optimistic assumptions on the pace of progress created disappointment and mistrust, now the investment community requests substantiated projections and realistic targets.

The *research questions* were defined after having analysed the major risk complexes impeding the marine energy market breakthrough. The aim of the research was to create strategic knowledge on how to mitigate or resolve them.

The *key original contribution* from the thesis is methodological. It comprises the use of a systematic and transparent approach for capturing, analysing and interpreting information obtained from expert stakeholders via a structured survey. The existing knowledge on how to prepare and achieve the market breakthrough of marine energy

sector is expanded. The results confirm that the systems thinking approach facilitates decision-making and that the concepts presented have the potential to substantiate strategic decisions by providing peer-group-based arguments. The value added by the research is given by the high credibility of the results as the findings were achieved in a traceable and understandable manner. The marine energy community can profit immediately from the leveraging of results, as the described strategy options can be directly integrated into strategic action plans. The findings help to improve the understanding that it is in the interest of all stakeholders to make best use of the present window of opportunity by intensified collaboration in order to move beyond the pre-profit phase and to jointly establish a new industrial sector.

The transdisciplinary research combines knowledge from the social and engineering sciences as well as from economics. Isolated knowledge is integrated and transparently processed to transform and improve approaches to problematic situations and challenging tasks arising in the course of commercialising the sector. In line with the principles of the systems approach, the research contributes to overcoming institutional and disciplinary boundaries by creating an open forum for confrontational debate and targeted solution finding. The findings cover the interests of renewable energy policy-makers, private and institutional investors, management and engineering consultancies, project developers and device manufacturers. As the elaborated methodology is not sector-specific, it can be applied in other fields in which orientating development trajectories is challenging due to a rapidly changing socio-political environment or by competing innovations.

The initial implications of the study require consideration of the identified milestones in order to precisely allocate time and effort. Without the fundamentally important ***government support***, the marine energy sector will not reach market competitiveness. Strong, consistent and stable political support is at present a key requirement for this sector. Government support mechanisms and subsidiary rules need to be in place for periods longer than twenty years as demonstrating a predictable policy framework is fundamental. Good examples are EU support programs and long-term feed-in tariff schemes that strengthen planning and support local governments by their job creation effects.

The study is the first to explicitly highlight the urgent need to showcase an *array-scale success* as the key interim milestone on the way towards commercial generation. By this event, the two interdependent top-ranked risk complexes “achieving funding” and “device reliability” will be simultaneously mitigated. As investor confidence depends on the proof of grid-connected operation, the attainment of the array-scale success is expected to trigger the investment required for large-scale deployment. Transparently demonstrating the maturity and commercial viability of the innovative generation concept means a significant de-risking of the industrial sector and the creation of decisive investor confidence. The correlated efforts for putting corresponding measures into practice are justified by the long-term expected return on investment after the market breakthrough. Where major industrial competitors understand and accept the significance of jointly clearing this milestone, the motivation for applying stakeholder-wide coordinated business and development strategies will increase. As the array-scale success and thus the start of the wholesale market roll-out need to be based on a number of equally competitive manufacturing firms, the remaining years before going to market allow sharing of knowledge in order to harden the technology.

Once the maturity and market competitiveness of the concept is proven, the development trajectory will adapt and the focus move towards *cost reduction*. Major benefits will be achieved by serial manufacturing and an improvement of efficiency in the course of the technology convergence process and by optimised asset management.

A number of innovative ideas and novel concepts were elaborated in the course of the research to mitigate or resolve underlying blocking issues. A novelty of this contribution is that prioritised strategy options are identified in a stakeholder-integrative and traceable manner. The identified main task of the *technology-driving stakeholders* is to improve device reliability and to reduce cost. In the course of the design and deployment of multi-device arrays, regular system functionality checks, targeting the final goal of grid-connected operation are recommended. The management of risk complexes, that affect the project performance either positively or negatively, needs to be a central task from the pre-feasibility stage through to decommissioning. Regarding the *policy framework*, the close and regular adaptation of public support programmes and incentive mechanisms to actual requirements is crucial for closely steering the development and commercialisation process. The

promotion of cross-interaction between renewables and the support of technologies with declared synergies towards offshore wind is elementary. Some of the stakeholders representing the *financing sector* outlined that the marine energy sector is characterised by a perception of high risk and high cost. The expensive deployment and significant cost of devices as well as long delays in projects coming on line are considered as counterproductive. To improve investor confidence, it is necessary to urgently demonstrate the market readiness. After this proof of concept, the financing sector will be in the position to foster large-scale deployment on an institutional level. As the cost of electricity is identified to be more relevant than capital expenditure, research efforts need to focus on identifying the long-term techno-economic optimum way for harvesting marine energy. When investigating *business development and strategy planning*, intensifying inter-firm cooperation and collaboration are seen as central targets. The limited sharing of knowledge is recognised as a major bottleneck to the development of the sector. Negotiating risk allocation and agreeing on appropriate risk sharing between stakeholders is key for realising efficient projects. Unrealistic risk distribution arrangements create additional cost and disturb the cross-linked implementation processes. Without a clearly defined risk distribution plan, either party is likely to manage uncertainty primarily for their own benefit, mostly to the disadvantage of others and to the project as a whole.

The research closes the *gap in literature* by providing a strategy-finding method based on the unbiased and transparent integration of cross-category stakeholder knowledge. The holistic approach allows the determination of the centre of gravity of a problem complex and the identification of case-specific strategies to resolve or mitigate it. To adequately address dynamically complex problems, the application of both abstract and case-specific knowledge is required. Iteratively combining multi-level expert interview data and system dynamics techniques allows strategies to fundamentally de-risk marine energy to be identified. Considering the multi-faceted technical, political and financial challenges that marine energy faces on the way towards commercial generation, a flexible and adaptable method like system dynamics is predestined to support the identification of robust strategies. Based on the encouraging results by the research, system dynamics is considered as an integral part of a decision support system aiming at advancing marine energy.

## **12.2 Recommendations**

### **12.2.1 Capturing of process image and sensitivity for dynamics trends**

To elaborate substantiated recommendations for facilitating the deployment of marine energy, it is necessary to regularly capture a realistic process image of the sector including actual tendencies and critical dynamics. As proven by the sensitivity analysis, time effects are of decisive relevance for the modelling output. Consequently, it is necessary to expand the expert interview basis towards capturing time-related correlations between the different impact factors, group terms and the target factors. By such an activity, a key advantage of the chosen calculating tool can be employed: the possibility to program time dependencies in order to more precisely configure the causal diagrams and to achieve realistic results.

Due to the rapid development of marine energy and the minor half-life period for knowledge in innovative sectors, a regular update of the database is recommended: every three years might be reasonable. The information gathering might be better realised via an internet-based survey to increase the number of interviewees. However, it needs to be considered that there is additional value in semi-structured personal interviews given the potential access to sensitive information and the academic quality.

As some of the identified prioritised strategy options were already under implementation at the time of finalising the study, it would be of interest to get feedback about positive and negative experience with their practicability and effectiveness; specifically, which strategies were successfully integrated into action plans and which were considered as inadequate or potentially counter-productive?

### **12.2.2 Co-projects for a symbiotic deployment with offshore wind**

Europe is leading in offshore wind deployment and marine energy development. The amount of investment in offshore wind and the corresponding upgrade of the grid is significant: 1,483 MW of new offshore wind capacity were connected in 2014 with an average turbine rating of 3.7 MW (European Wind Energy Association, 2014). About 26 GW of consented offshore wind farms in Europe are identified for the future. Dealing with similar dimensions, the European Network of Transmission System Operators for Electricity (ENTSO-E, 2014) has published a 10-year network development plan in which the total investment cost for the portfolio of pan-European



projects amounts to €150 billion (Bucher, 2015). One third of the new grid assets are subsea. Taking into account these figures and the fact that there is a high correlation between good offshore wind and wave sites, the connection of high capacity marine energy converters to grid will become possible without major technical modifications by increasing the rating of the offshore wind converter stations and power take-off systems accordingly. Recent research focuses on combining wave energy and offshore wind (Pérez-Collazo, Greaves and Iglesias, 2015; Azzellino et al., 2013; Veigas, Carballoa and Iglesias, 2014; ORECCA, 2016; Rusu and Onea, 2017) as well as on connecting tidal current turbines to the future offshore grid (Gorenstein Dedecca and Hakvoort, 2016; Zanuttigh et al., 2016).

The realistic chance to participate in co-projects (offshore wind & marine energy) might create additional motivation for the device manufacturers to enter into inter-firm cooperation outside the marine energy context, aiming at jointly developing a further carbon-free power-generating alternative.

### **12.3 Final thoughts**

In the course of the global energy transition, the power infrastructure is subject to fundamental change taking place at unprecedented speed. Today, solar PV and wind are the fastest-growing sources of power generation with record-low auction prices of 3 to 5 c€/kWh for PV (IEA, 2016 and IEA, 2017) and 5 to 7 c€/kWh for offshore wind (De Pee, Küster and Schlosser, 2017). Green and Newman (2017) show that in certain locations electricity from rooftop-installed solar PV in combination with household battery storage became cheaper than commonly charged utility tariffs. Within such a turbulent environment, marine energy needs to make use of the window of opportunity to rapidly prove market readiness and to become one part of the future energy mix.

The capability to identify and manage dynamic complexity, inherent to disruptive innovation, is one of the strategic tasks of our time. Trans-disciplinary thinking supported by systematic data analytics and machine learning routines allow unprecedented insight and the reliable determination of long-term successful strategies.

It remains to conclude that “tendencies are more important than absolute values”.

## 13 REFERENCES

- Ahern, T., Leavy, B. (2014) Complex project management as complex problem-solving, *International Journal of Project Management* 32, pp1371–1381
- Alkemade, F., Kleinschmidt, C., Hekkert, M. (2007) Analysing emerging innovation systems: A functions approach to foresight, *International Journal of Foresight and Innovation Policy* 3, pp139–68
- Allan, G. (2003) A critique of using grounded theory as a research method, *Electronic Journal of Business Research Methods* 2(1), pp1–10
- Alpha Ventus (2011) *Operation offshore*, BVA Bielefelder Verlag, ISBN 978-3-87073-479-4
- Al-Reshaid, K., Kartam, N. (2005) Design-build pre-qualification and tendering approach for public projects, *International Journal of Project Management* 23, pp309–320, <http://dx.doi.org/10.1016/j.ijproman.2004.11.004>
- Amanatidou, E., Guy, K. (2008) Interpreting foresight process impacts: Steps towards the development of a framework conceptualising the dynamics of foresight systems, *Technological Forecasting and Social Change* 75, pp539–557
- Andersson, B.A., Jacobsson, S. (2000) Monitoring and assessing technology choice: The case of solar cells, *Energy Policy* 28, pp1037–1049
- Ansari X-prize (2004) Composite spacecraft wins X-prize, *Reinforced Plastics* 48(10)
- Arthur, W.B. (1999) Complexity and the economy, *Science* 284, pp107–109
- Atkinson, R., Crawford, L., Ward, S. (2006) Fundamental uncertainties in projects and the scope of project management, *International Journal of Project Management* 24, pp687–698, <http://dx.doi.org/10.1016/j.ijproman.2006.09.011>
- Attoh-Okine, N. (2002) Probabilistic analysis of factors affecting highway construction costs: A belief network approach, *Canadian Journal of Civil Engineering* 29(3), pp369–374
- Attwater, W., Hase, S. (2013) *Convergent interviewing and its use in qualitative research*, University of Otago, New Zealand
- Augustine, M., Yadav, O.P., Jain, R., Rathore, A.P.S. (2010) Concept convergence process: A framework for improving product concepts, *Computers and Industrial Engineering* 59, pp367–377
- Azzellino, A., Ferrante, V., Kofoed, J.P., Lanfredi, C., Vicinanza, D. (2013) Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach, *International Journal of Marine Energy* 3–4, pp11–25
- Barlow, J. (2000) Innovation and learning in complex offshore construction projects, *Research Policy* 29, pp973–989
- Bayod-Rújula, A.A. (2009) Future development of the electricity systems with distributed generation, *Energy* 34, pp377–383
- Bennett, R.H. (1998) The important of tacit knowledge in strategic deliberations and decisions, *Management Decision* 36(9), pp589–597

- Bergek, A., Hekkert, M., Jacobsson, S. (2008) Functions in innovation systems: A framework for analysing energy system dynamics, Working Paper 84426-008, Institute for Management of Innovation and Technology, Göteborg, Sweden
- Bertaux, D. (1981) From the life-history approach to the transformation of sociological practice, *Biography and Society*, pp29–45, Sage, London
- Bhave, A.G., Mishra, A., Raghuwanshi, N.S. (2014) A combined bottom-up and top-down approach for assessment of climate change adaptation options, *Journal of Hydrology* 518, pp150–161
- Bittencourt Ferreira, C., Zarraonandia, G. (2015) The new DNV GL Standard for Tidal Energy Converters, Proceedings of the 11<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC), ISSN 2309-1983, Nantes, France
- Bonar, P.A.J., Bryden, I.G., Borthwick, A.G.L. (2015) Social and ecological impacts of marine energy development, *Renewable and Sustainable Energy Reviews* 47, pp486–495
- Bouncken, R.B., Kraus, S. (2013) Innovation in knowledge-intensive industries: The double-edged sword of co-opetition, *Journal of Business Research* 66, pp2060–2070, <http://dx.doi.org/10.1016/j.jbusres.2013.02.032>
- Bourreau, M., Doğan, P. (2010) Cooperation in product development and process R&D between competitors, *International Journal of Industrial Organization* 28, pp176–190, <http://dx.doi.org/10.1016/j.ijindorg.2009.07.010>
- Brink, T. (2017) Small and medium-sized enterprise routes for innovation collaboration with larger enterprises, *Industrial Marketing Management* 64, pp122–134
- Brown, S.L., Eisenhardt, K.M. (1997) The art of continuous change: Linking complexity theory and time-paced evolution in shifting organizations, *Administrative Science Quarterly* 42(1), pp1–34
- Bucher, R. (2008) Numerical power extraction modelling for the Wando 600 MW tidal current plant including a subsequent impact assessment on the marine main currents, Proceedings of the HydroVision Conference, Sacramento, USA
- Bucher, R. (2009a) Maximising the energy yield of tidal stream plants, *International Journal on Hydropower and Dams* 4, pp88–92, Aqua Media International Ltd., UK
- Bucher, R. (2009b) Tidal regime modelling and energy yield calculation for a tidal array, Proceedings of the Annual Conference on Hydraulic Engineering (Issue 39), ISBN 978-3-86780-101-0, pp117–132, Dresden Technical University, Germany
- Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, Proceedings of the 4<sup>th</sup> International Conference on Ocean Energy (ICOE), Dublin, Ireland
- Bucher, R. (2013) Strategic risk management in ocean energy: A system dynamics approach to the evaluation of 40+ expert interviews, Proceedings of the 10<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC), Aalborg, Denmark

- Bucher, R. (2014) *Energy Yield Optimisation for a 600 MW Tidal Array*, Lambert Academic Publishing, ISBN 978-3-659-61381-4
- Bucher, R. (2015) The role of pumped-storage in a pan-European supergrid, *The International Journal on Hydropower and Dams* 5, pp46–48, ISSN 1352-2523
- Bucher, R., Bryden, I.G. (2014a) Strategic orientation for the ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge, *Journal of Energy Challenges and Mechanics*, Vol. 1(2) article 8, pp103–112, ISSN 2056-9386
- Bucher, R., Bryden, I.G. (2014b) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, *Proceedings of the 2<sup>nd</sup> Asian Wave and Tidal Energy Conference (AWTEC)*, Tokyo, Japan
- Bucher, R., Bryden, I.G. (2015) Governing the market entry of marine energy by symptom-adapted interventions: (i) Reduction of detail complexity; and (ii) Managing dynamically complex tasks, *Journal of Energy Challenges and Mechanics*, Vol. 2(2) article 4, pp56–61, ISSN 2056-9386
- Bucher, R., Bryden, I.G. (2016) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, *International Journal of Marine Energy*, *International Journal of Marine Energy*, Vol. 13, pp180–192, <http://dx.doi.org/10.1016/j.ijome.2015.05.002>
- Bucher, R., Couch, S.J. (2011) Adjusting the financial risk of tidal current projects by optimising the “installed capacity / capacity factor” - ratio already during the feasibility stage, *Proceedings of the 9<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK
- Bucher, R., Couch, S.J. (2013) Adjusting the financial risk of tidal current projects by optimising the “installed capacity / capacity factor” - ratio already during the feasibility stage, *International Journal of Marine Energy*, Vol. 2, pp24–42, ISSN 2214-1669, <http://dx.doi.org/10.1016/j.ijome.2013.05.008>
- Bucher, R., Jeffrey, H. (2014) Creation of investor confidence: The top-level drivers for reaching maturity, *Proceedings of the 5<sup>th</sup> International Conference on Ocean Energy (ICOE)*, Halifax, Canada
- Bucher, R., Jeffrey, H. (2015) The strategic objective of competitive collaboration: Managing the solid market launch of marine energy, *Proceedings of the 11<sup>th</sup> European Wave and Tidal Energy Conference (EWTEC)*, ISSN 2309-1983, Nantes, France
- Bucher, R., Jeffrey, H., Bryden, I.G., Harrison, G.P. (2016) Creation of investor confidence: The top-level drivers for reaching maturity in marine energy, *Renewable Energy* 88, pp120–129, <http://dx.doi.org/10.1016/j.renene.2015.11.033>
- Burney, S.M. (2008) *Inductive and deductive research approach*, Department of Computer Science, University of Karachi, India
- Capra, F. (1996) *The web of life: A new scientific understanding of living systems*, New York, Anchor Books, ISBN 978-03-85476-76-8, p30
- Carbon Trust (2011) *Accelerating marine energy: The potential for cost reduction*, The Carbon Trust, London, UK

- Carlsson, B., Jacobsson, S., Holmén, M., Rickne, A. (2002) Innovation systems: Analytical and methodological issues, *Research Policy* 31, pp233–245
- Catapult (2016) Wave Energy Scotland – Application of technologies landscaping study, <https://ore.catapult.org.uk/our-knowledge-areas/> [26/09/2017]
- Cassiman, B., Di Guardo, M.C., Valentini, G. (2009) Profit from innovation: Insights from co-opetition, *Long Range Planning* 42, pp216–233, <http://dx.doi.org/10.1016/j.lrp.2009.01.001>
- Chaerul, M., Tanaka, M., Shekdar, A. (2008) A system dynamics approach for hospital waste management, *Waste Management* 28 (2), pp442–449
- Cooper, K., Lee, G. (2009) Managing the dynamics of projects and changes at Fluor, *Proceedings of the International System Dynamics Conference*, System Dynamics Society, Albuquerque, USA
- Corsatea, T.D. (2014) Increasing synergies between institutions and technology developers: Lessons from marine energy, *Energy Policy* 74, pp682–696
- Crespi, V., Galstyan, A., Lerman, K. (2008) Top-down versus bottom-up methodologies in multi-agent system design, *Autonomous Robots* 24(3), pp303–313
- Creswell, J. (1998) *Qualitative inquiry and research design: Choosing among five traditions*, Thousand Oaks, CA, ISBN 978-14-12916-06-6
- Culley, D.M., Funke, S.W., Kramer, S.C., Piggott, M.D. (2016) Integration of cost modelling within the micro-siting design optimisation of tidal turbine arrays, *Renewable Energy* 85, pp215–227
- Daimler (2013) Daimler, Nissan, Ford join forces to develop affordable FCEVs, *Fuel Cells Bulletin* 2, Elsevier Ltd., pp2–3
- DARPA (2007) Defense Advanced Research Projects Agency Urban Challenge, [www.darpa.mil/grandchallenge](http://www.darpa.mil/grandchallenge) [26/10/2010]
- Davidson, C. (2016) Marine energy: Key steps to maintain a Great British success story, *Highlands and Islands Enterprise*, [www.hie.co.uk](http://www.hie.co.uk) [24/10/2017]
- Dean, J.W., Sharfman, M.P. (1993) Procedural rationality in strategic decision-making, *Journal of Management Studies* 30, pp587–610
- Del Río, P., Bleda, M. (2012) Comparing the innovation effects of support schemes for renewable electricity technologies: a function of innovation approach, *Energy Policy* 50, pp272–282
- Department of Energy & Climate Change (2008) *Climate Change Act*, UK Government, London, UK
- Department of Energy & Climate Change (2011) *UK renewable energy roadmap*, UK Government, London, UK
- De Pee, A., Küster, F., Schlosser, A. (2017) Winds of change? Why offshore wind might be the next big thing, *McKinsey & Company*, <https://www.mckinsey.com> [03.11.2017]
- Dick, B. (1998) Convergent interviewing: A technique for qualitative data collection, [www.aral.com.au/resources/iview.html](http://www.aral.com.au/resources/iview.html) [29.07.2015]

- Diehl, E., Sterman, J.D. (1995) Effects of feedback complexity on dynamic decision-making, *Organizational Behavior and Human Decision Processes* 62(2), pp198–215
- Dixit, A.K., Nalebuff, B.J. (1991) *Thinking strategically*, ISBN 978-03-93310-35-1, pp36–37
- DNV (2008) Certification of tidal and wave energy converters, Offshore service specification DNV-OSS-312, [www.dnv.com](http://www.dnv.com) [22.07.2015]
- Doorley, T.L. (1993) Teaming up for success, *Business Quarterly* 57, pp99–103
- Elkady, G., Moizer, J., Liu, S. (2014) A decision support framework to assess grocery retail supply chain collaboration: The system dynamics modelling approach, *International Journal of Innovation, Management and Technology* 5(4), <http://dx.doi.org/10.7763/ijimt.2014.v5.519>
- El-Sawalhi, N., Eaton, D., Rustom, R. (2007) Contractor pre-qualification model: State-of-the-art, *International Journal of Project Management* 25, pp465–474, <http://dx.doi.org/10.1016/j.ijproman.2006.11.011>
- EMEC (2009a) Assessment of performance of tidal energy conversion systems, ISBN 978-0-580-65031-4
- EMEC (2009b) Guidelines for marine energy converter certification schemes, ISBN 978-0-580-65040-6
- EMEC (2009c) Guidelines for project development in the marine energy industry, ISBN 978-0-580-67033-6
- ENGIE (2016) The ENGIE tidal power pilot farm raz Blanchard, [www.engie.com/wp-content/uploads/2015/05/parc-hydro2.jpg](http://www.engie.com/wp-content/uploads/2015/05/parc-hydro2.jpg) [gdfsuez.com](http://gdfsuez.com) [26/09/2016]
- Engwall, M. (1998) *The project concept(s): On the unit of analysis in the study of project management*, Kluwer, Boston, USA, pp25–35
- ENTSO-E (2014) 10-year network development plan, [www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2014](http://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2014) [11.02.2015]
- Erickson, W.B., Maitland, I. (1989) *Healthy industries and public policy*, Dutton, M.E. (ed.), Pergamon Press, New York, USA
- Ernst & Young (2013) *Rising tide: Global trends in the emerging ocean energy market*, [www.ey.com/Publication/vwLUAssets/EY-Ocean-energy-Rising-tide-2013/\\$FILE/EY-Ocean-energy-Rising-tide-2013.pdf](http://www.ey.com/Publication/vwLUAssets/EY-Ocean-energy-Rising-tide-2013/$FILE/EY-Ocean-energy-Rising-tide-2013.pdf) [10.07.2016]
- EU (2008) *The 2°C target: Background on impacts, emission pathways, mitigation options and costs*, EU Climate Change Expert Group, EG Science
- European Commission (2011) *UpWind: Integrated wind turbine design*, <http://ec.europa.eu/research/energy> [05/05/2015]
- European Commission (2014a) *Ocean energy: Action needed to deliver on the potential of ocean energy by 2020 and beyond*, <http://ec.europa.eu/maritimeaffairs/policy> [05/05/2015]
- European Commission (2014b) *Blue energy: Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond*, <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0008> [25/09/2015]

- European Commission (2015) Ocean energy status report, Joint Research Centre, Institute for Energy and Transport, <http://dx.doi.org/10.2790/866387>, ISBN 978-92-79-44611-5
- European Ocean Energy Association (2013) Industry vision paper, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- European Wind Energy Association (2014) The European offshore wind industry: Key trends and statistics, [www.ewea.org](http://www.ewea.org) [30/03/2016]
- Eurostat (2016) Renewable energy statistics, [http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable\\_energy\\_statistics](http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics) [03/04/2016]
- Federal Ministry for Economic Affairs and Energy of Germany (2007) 11<sup>th</sup> Asia-Pacific Conference of German Business, [www.bmwi.de/EN/Press](http://www.bmwi.de/EN/Press) [03/08/2008]
- FIDIC (2010) Estonia Seminar: Policy and contract trends, Fédération Internationale des Ingénieurs-Conseils, France
- Formentini, M., Romano, P. (2011) Using value analysis to support knowledge transfer in the multi-project setting, *International Journal of Production Economics* 131, pp545–560
- Forrester, J.W. (1961) *Industrial dynamics*, The MIT Press, Massachusetts Institute of Technology, Cambridge, USA
- Forrester, J.W. (1971) Counterintuitive behaviour of social systems, *Technology Review* 73(3), pp52–68
- Fraunhofer (2013) Levelised cost of electricity, Renewable energy technologies, Institute for Solar Energy Systems, [www.ise.fraunhofer.de](http://www.ise.fraunhofer.de) [06/04/2014]
- Frigo, M.L., Anderson, R.J. (2009) Strategic risk assessment: A first step for improving risk management and governance, *Strategic Finance*, pp25–33
- G7 Summit (2015) Leaders' Declaration, 7–8 June 2015, [www.bundesregierung.de](http://www.bundesregierung.de) [19.07.2015]
- Galvin, R. (2015) How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? *Journal of Building Engineering*, pp2–12
- Gamesa (2014) Ending of the Azimut project that will enable the development of a 15 MW offshore wind turbine in 2020, [www.gamesacorp.com](http://www.gamesacorp.com) [05/05/2015]
- GDF SUEZ (2014) France selects GDF SUEZ to build a pilot tidal power farm in the Alderney Race, [www.gdfsuez.com](http://www.gdfsuez.com) [02/05/2015]
- Geels, F.W. (2004) From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory, *Research Policy* 33, pp897–920
- Geels, F.W., Kemp, R. (2007) Dynamics in socio-technical systems: Typology of change processes and contrasting case studies, *Technology in Society* 29(4), pp441–455
- Girard, C., Pulido-Velazquez, M., Rinaudo, J.-D., Pagé, C., Caballero, Y. (2015) Integrating top-down and bottom-up approaches to design global change adaptation

at the river basin scale, *Global Environmental Change* 34, pp132–146, <http://dx.doi.org/10.1016/j.gloenvcha.2015.07.002>

Global Wind Report (2014) Annual market update, [www.gwec.net](http://www.gwec.net) [06/05/2014]

Gnyawali, D.R., Park, B.-J. (2011) Co-opetition between giants: Collaboration with competitors for technological innovation, *Research Policy* 40, pp650–663, <http://dx.doi.org/10.1016/j.respol.2011.01.009>

Gorenstein Dedecca, J., Hakvoort, R.A. (2016) A review of the North Seas offshore grid modeling: Current and future research, *Renewable and Sustainable Energy Reviews* 60, pp129–143

Grant, R.M., Baden-Fuller, C. (2004) A Knowledge Accessing Theory of Strategic Alliances, *Journal of Management Studies* 41, ISSN 1467-6486

Green, J., Newman, P. (2017) Citizen utilities: The emerging power paradigm, *Energy Policy* 105, pp283–293

Groesser, S. (2011a) Projects fail because of dynamic complexity: Managing complexity by qualitative feedback modelling, *Projektmanagement aktuell* 22(5), Bern University of Applied Sciences, Switzerland, pp18–25

Groesser, S. (2011b) Measuring the degree of dynamic complexity in differential equation simulation models, *Proceedings of the 29<sup>th</sup> International System Dynamics Conference*, Washington DC, USA

Groesser, S. (2012) Dynamic complexity is the major challenge for the management, *CFO aktuell* 6(2), Switzerland, pp67–72

Guest, G., Bunce, A., Johnson, L. (2006) How many interviews are enough? An experiment with data saturation and variability, *Field Methods* 18(1) pp59–82

Gunn, K., Stock-Williams, C. (2012) Quantifying the global wave power resource, *Renewable Energy* 44, pp296–304

Håkansson, H. (1990) Technological collaboration in industrial networks, *European Management Journal* 8(3), pp371–379

Hamel, G., Doz, Y.L., Prahalad, C.K. (1989) Collaborate with your competitors and win, *Harvard Business Review* 67(1), pp133–139

Hammons, T.J. (2008) Integrating renewable energy sources into European grids, *International Journal of Electrical Power and Energy Systems* 30, pp462–475

Hayek, F.A. (1945) The use of knowledge in society, *American Economic Review* 35(4), pp519–530

Hekkert, M.P. (2007) Functions of innovation systems: A new approach for analysing technological change, *Technological Forecasting and Social Change* 74, pp413–432

Holler, J.R. (2014) System Dynamics Analysis of the Growth and Management of a Graduate Robotics Lab, Master thesis, Virginia Polytechnic Institute and State, USA

Huang, J.C., Newell, S. (2003) Knowledge integration processes and dynamics within the context of cross-functional projects, *International Journal of Project Management* 21, pp167–176



- Hull, F., Slowinski, E. (1990) Partnering with technology entrepreneurs, *Research Technology Management* (11/12), pp16–20
- Huse, J.A. (2000) Understanding and negotiating turnkey and EPC contracts, Sweet & Maxwell Ltd, London, ISBN 978-04-21674-10-3
- IEA (2008) Energy technology perspectives: Scenarios and strategies to 2050, OECD/IEA, Paris, France
- IEA (2012a) World Energy Outlook, [www.worldenergyoutlook.org](http://www.worldenergyoutlook.org) [21.01.2013]
- IEA (2012b) Key World Energy Statistics, OECD/IEA, Paris, France
- IEA (2013) Technology Roadmap Wind Energy, [www.iea.org/publications](http://www.iea.org/publications) [06/05/2014]
- IEA (2015) World Energy Outlook 2015: Special Report on Energy and Climate, [www.iea.org/publications](http://www.iea.org/publications) [22.07.2015]
- IEA (2016) Next Generation Wind and Solar Power: From cost to value, [www.iea.org/publications](http://www.iea.org/publications) [28.09.2015]
- IEA (2017) Renewable 2017: Analysis and forecasts to 2022, [www.iea.org/publications](http://www.iea.org/publications) [06.10.2017]
- IEA/OECD (2007) Energy technologies at the cutting edge, International Energy Technology Collaboration, [https://www.iea.org/publications/freepublications/publication/Cutting\\_Edge\\_2007\\_WEB.pdf](https://www.iea.org/publications/freepublications/publication/Cutting_Edge_2007_WEB.pdf) [16.10.2017]
- IEA-OES (2013) Annual report, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2014]
- IEA-OES (2014a) Annual report, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [01/05/2015]
- IEA-OES (2014b) Review of supporting policies, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2013]
- IER (2010) Global fossil fuel and renewable subsidies oil, [www.instituteeforenergyresearch.org](http://www.instituteeforenergyresearch.org) [28/02/2013]
- Interaction Design Foundation (2014) The Encyclopaedia of Human-Computer Interaction, 2<sup>nd</sup> Edition, ISBN 978-87-92964-00-7, Aarhus, Denmark
- IRENA (2012) International Renewable Energy Agency, Renewable energy technologies: Cost analysis series, p47, [www.irena.org](http://www.irena.org) [10/04/2014]
- IRENA (2014) International Renewable Energy Agency, Tidal energy: Technology brief, p23, [www.irena.org](http://www.irena.org) [23/07/2015]
- ISO (2009) International Organization for Standardization, ISO 31000, Risk management: Principles and guidelines, [www.iso.org](http://www.iso.org) [05/02/2016]
- Išoraitė, M. (2009) Importance of strategic alliances in company's activity, *Intellectual Economics* 1(5), ISSN 1822-8011, pp39–46
- Jacobsson, S., Bergek, A. (2004) Transforming the energy sector: The evolution of technological systems in renewable energy technology, *Industrial and Corporate Change* 13(5), pp815–849

- Jay, B., Jeffrey, H. (2010) UKERC Research Atlas Topic: Marine Energy, UK Energy Research Centre, London
- Jeffrey, H., Jay, B., Winskel, M. (2013) Accelerating the development of marine energy: Exploring the prospects, benefits and challenges, *Technological Forecasting and Social Change* 80, pp1306–1316
- Johnstone, N., Haščič, I., Popp, D., (2010) Renewable energy policies and technological innovation: Evidence based on patent counts, *Environmental & Resource Economics* 45(1), pp133–155
- Kaplan, S., Tripsas, M. (2008) Thinking about technology: Applying cognitive lens to technical change, *Research Policy* 37(5), pp790–805
- Karikari-Boateng, K.A., Grimwade, J., Johanning, L., Mueller, M.A., Barltrop, N. (2013) Reliability of Tidal Turbines using Wind Turbine Experience, *Proceedings of the 10th European Wave and Tidal Energy Conference*, Aalborg, Denmark
- Kerr, S., Watts, L., Colton, J., Conway, F., Hull, A., Johnson, K., Jude, S., Kannen, A., MacDougall, S., McLachlan, C., Potts, T., Vergunst, J. (2014) Establishing an agenda for social studies research in marine renewable energy *Energy Policy* 67, pp694–702
- Khaled, A.-R., Nabil, K. (2005) Design-build pre-qualification and tendering approach for public projects, *International Journal of Project Management* 23, pp309–320, <http://dx.doi.org/10.1016/j.ijproman.2004.11.004>
- Kim, Y.H., Sting, F.J., Loch, C.H. (2014) Top-down, bottom-up, or both? Toward an integrative perspective on operations strategy formation, *Journal of Operations Management* 32, pp462–474, <http://dx.doi.org/10.1016/j.jom.2014.09.005>
- Kirkwood, C.W. (1998) *System dynamics methods: A quick introduction*, College of Business, Arizona State University, USA
- Komendantova, N., Patt, A., Barras, L., Battaglini, A. (2009) Perception of risks in renewable energy projects: The case of concentrated solar power in Africa, *Energy Policy* 40, pp103–109
- KPMG (2011) *Confronting complexity: Research findings and insights*, KPMG International, [www.kpmg.com](http://www.kpmg.com) [25.11.2015]
- Lai, C.S., McCulloch, M.D. (2017) Levelized cost of electricity for solar photovoltaic and electrical energy storage, *Applied Energy* 190, pp191–203
- Larsson, R., Bengtsson, L., Henriksson, K., Sparks, J. (1998) The inter-organizational learning dilemma: Collective knowledge development in strategic alliances, *Organization Science* 9(3), pp286–305
- Leete, S., Xu, J., Wheeler, D. (2013) Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences, *Energy Policy* 60, pp866–875
- Le Parisien (2017) *Énergie électrique: Un vaste projet d'hydroliennes suspendu dans la Manche*, <http://www.leparisien.fr/economie/energie-electrique-un-vaste-projet-d-hydroliennes-suspendu-dans-la-manche-09-01-2017-6543522.php> [13/11/2017]

- Lewis, M., Neill, S.P., Robins, P.E., Hashemi, M.R. (2015) Resource assessment for future generations of tidal-stream energy arrays, *Energy* 83, pp403–415
- Lhuillery, S., Pfister, E. (2009) R&D cooperation and failures in innovation projects: Empirical evidence from French CIS data, *Research Policy* 38, pp45–57
- Li, F., Dong, S., Li, Z., Li, Y., Li, S., Wan, Y. (2012) The improvement of CO<sub>2</sub> emission reduction policies based on system dynamics method in traditional industrial region with large CO<sub>2</sub> emission, *Energy Policy* 51, pp683–695, <http://dx.doi.org/10.1016/j.enpol.2012.09.014>
- Lincoln, Y.S., Guba, E. G. (1985) *Naturalistic inquiry*, Sage Publications, ISBN 978-0-80392-431-4
- Low Carbon Innovation Co-ordination Group (2012) *Marine energy summary report: Technology innovation needs assessment*, UK
- Lyneis, J.M. (1999) System dynamics for business strategy: A phased approach, *System Dynamics Review* 15(1), pp37–70
- Macalister, T. (2011) UK marine energy sector could be worth £76bn and support 68,000 jobs, *The Guardian*, <https://www.theguardian.com/business/2011/may/02/wave-power-tidal-energy-carbon> [11/01/2017]
- MacDougall S.L. (2017) Confronting the financing impasse: Risk management through internationally staged investments in tidal energy development, *International Journal of Marine Energy* 18, pp78–87
- MacGillivray, A., Jeffrey, H., Winskel, M., Bryden, I.G. (2014) Innovation and cost reduction for marine renewable energy: A learning investment sensitivity analysis, *Technological Forecasting and Social Change* 87, pp108–124
- Magagna, D., Uihlein, A. (2015) Ocean energy development in Europe: Current status and future perspectives, *International Journal of Marine Energy* 56, <http://dx.doi.org/10.1016/j.ijome.2015.05.001>
- Mainzer, K. (1999) *Komplexe Systeme und Nichtlineare Dynamik in Natur und Gesellschaft*, Springer Publishing Company, ISBN 978-3-540-65329-5, pp23–24
- Marine Scotland (2014) Licence for marine renewables construction works (Inner Sound / Pentland Firth), [www.gov.scot](http://www.gov.scot) [03/05/2015]
- Marine Scotland (2015) Consent granted to construct and operate the Sound of Islay demonstration tidal array electricity generating station, [www.gov.scot](http://www.gov.scot) [03/05/2015]
- Markard, J., Stadelmann, M., Truffer, B. (2009) Prospective analysis of technological innovation systems: Identifying technological and organizational development options for biogas in Switzerland, *Research Policy* 38, pp655–667, <http://dx.doi.org/10.1016/j.respol.2009.01.013>
- Martin, P.Y., Turner, B.A. (1986) Grounded theory and organizational research, *Journal of Applied Behavioural Science* 22(2), p141, <http://dx.doi.org/10.1177/002188638602200207>
- Masini, A., Menichetti, E. (2012) The impact of behavioural factors in the renewable energy investment decision-making process: Conceptual framework and empirical findings, *Energy Policy* 40, pp28–38

- McSweeney, J. (2012) Ocean energy: Harnessing the potential, Proceedings of the 4<sup>th</sup> International Conference on Ocean Energy, Dublin, Ireland
- MeyGen (2014) £51 million MeyGen financial close completed, [www.meygen.com](http://www.meygen.com) [03/05/2015]
- MeyGen (2016) Turbine technology & testing, [www.meygen.com](http://www.meygen.com) [15/08/2016]
- MHI Vestas Offshore (2015) Leading edge technology: The V164-8.0 MW<sup>®</sup> Turbine, [www.mhivestasoffshore.com](http://www.mhivestasoffshore.com) [04/05/2015]
- Miller, R.G., Hutchison, Z.L., Macleod, A.K., Burrows, M.T., Cook, E.J., Last, K.S., Wilson, B. (2013) Marine renewable energy development: Assessing the benthic footprint at multiple scales, *Frontiers in the Ecology and Environment* 11, pp433–440
- Moghaddama, N. (2012) Formulating industry strategies, *Renewable Energy* 39, pp299–306
- Morse, J.M. (1994) Designing funded qualitative research, *Handbook of qualitative research*, pp220–235, Thousand Oaks, CA, Sage Publications
- Morse, J.M. (1995) The significance of saturation, *Qualitative Health Research* 5, pp147–149
- MRIA (2011) Marine Renewables Industry Association: A review of Research and Development in Ocean Energy in the Republic of Ireland, <http://www.mria.ie/documents/eab9e47fbd94a9101fff94623.pdf>, [12.10.2017]
- Murmann, J.P., Frenken, K. (2006) Toward a systematic framework for research on dominant designs, technological innovations and industrial change, *Research Policy* 35, pp925–952
- Nature (2016) China's carbon emissions could peak sooner than forecast, [www.nature.com](http://www.nature.com) [10.11.2016]
- Negro, S.O. (2007) Dynamics of technological innovation systems: The case of biomass energy, Dissertation, ISSN: 0169-4839, Utrecht University, Netherlands
- Negro, S.O., Alkemade, F., Hekkert, M.P. (2012) Why does renewable energy diffuse so slowly? A review of innovation system problems, *Renewable and Sustainable Energy Reviews* 16, pp3836–3846
- Neill, S.P., Vögler, A., Goward-Brown, A.J., Baston, S., Lewis, M.J., Gillibrand, P.A., Waldman, S., Woolf, D.K. (2017) The wave and tidal resource of Scotland, *Renewable Energy* 114, pp3–17
- Nelson, R.R. (1989) Understanding technical change as an evolutionary process, *Journal of Economic Behavior and Organization* 11(3), pp450–453
- Nonaka, I., Takeuchi, H. (1995) *The knowledge creating company: How Japanese companies create the dynamics of innovation*, Oxford University Press, pp125–127
- Okhuysen, G.A., Eisenhardt, K.M. (2002) Integrating knowledge in groups: How formal interventions enable flexibility, *Organisation Science* 13 (4), pp370–386
- ORECCA (2016) Offshore Renewable Energy Conversion platforms, Coordination Action, [www.orecca.eu](http://www.orecca.eu) [31.01.2016]

- Otto, P. (2008) A system dynamics model as a decision aid in evaluating and communicating complex market entry strategies, *Journal of Business Research* 61, pp1173–1181, <http://dx.doi.org/10.1016/j.jbusres.2007.11.013>
- Oviedo-Ocaña, E.R., Dominguez, I., Torres-Lozada, P., Marmolejo-Rebell, L.F., Komilis, D., Sanchez, A. (2016) A qualitative model to evaluate biowaste composting management systems using causal diagrams, *Journal of Cleaner Production* 133, pp201–211, <http://dx.doi.org/10.1016/j.jclepro.2016.05.115>
- Pérez-Collazo, C., Greaves, D., Iglesias, G. (2015) A review of combined wave and offshore wind energy, *Renewable and Sustainable Energy Reviews* 42, pp141–153
- Previsic, M., Epler, J., Hand, M., Heimiller, D., Short, W., Eurek, K. (2012) The future potential of wave power in the US, American Geophysical Union, Abstract #OS53D-08, [www.re-vision.net](http://www.re-vision.net) [06/04/2014]
- Previsic, M., Shoele, K. (2013) Cost reduction pathways for wave energy, 10<sup>th</sup> European Wave and Tidal Energy Conference, Aalborg, Denmark
- Proff, H. (2013) Geschäftsmodelle zwischen technischen Herausforderungen und betriebswirtschaftlichen Notwendigkeiten, Axel Springer Group, <http://dx.doi.org/10.1007/978-3-658-01817-7>
- Radzicki, M.J., Taylor, R.A. (2008) Origin of System Dynamics: Jay W. Forrester and the History of System Dynamics, U.S. Department of Energy's Introduction to System Dynamics
- Rapoport, A. (1986) General system theory: Essential concepts and applications, Cybernetics and systems series, Abacus Press, Kent, UK
- Remington, K. (2011) Leading complex projects: Comprehend complexity, Gower Publishing, ISBN 978-14-09419-05-1
- RenewableUK (2013) Wave and tidal energy in the UK, [www.renewableuk.com](http://www.renewableuk.com) [13/02/2013]
- Richards, G., Noble, B., Belcher, K. (2012) Barriers to renewable energy development: A case study of large-scale wind energy in Saskatchewan, Canada, *Energy Policy* 42, pp691–698
- Richardson, G.P. (1997) Problems in causal loop diagrams revisited, *System Dynamics Review* 13(3), pp247–252
- Richardson, G.P. (2006) Concept models, Proceedings of the 24<sup>th</sup> International Conference of the System Dynamics Society, Nijmegen, Netherlands
- Richardson, G.P., Sterman, J.D. (1996) System Dynamics '96, Proceedings of the International System Dynamics Conference, System Dynamics Society, USA
- RIMS (2011) Why strategic risk management? Risk and Insurance Management Society, New York, USA
- Rind, D. (1999) Complexity and climate, *Science* 284(105), pp105–107
- Ritala, P., Hurmelinna-Laukkanen, P. (2009) What's in it for me? Creating and appropriating value in innovation-related co-opetition, *Technovation* 29, pp819–828

- Roberts, A., Wallace, W., McClure, N. (2003) Strategic risk management, Heriot-Watt University, Edinburgh, UK
- Roussel, C.S., Deltour, F. (2012) Beyond cross-functional teams: Knowledge integration during organisational projects and the role of social capital, *Knowledge Management Research and Practice* 10, pp128–140
- Rusu, L., Onea, F. (2017) The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power, *Renewable and Sustainable Energy Reviews* 75, pp1348–1362
- Rycroft, R.W. (2007) Does cooperation absorb complexity? Innovation networks and the speed and spread of complex technological innovation, *Technological Forecasting and Social Change* 74, pp565–578
- Santos, L., Soares, I., Mendes, C., Ferreira, P. (2014) Real Options versus traditional methods to assess renewable energy projects, *Renewable Energy* 68, pp588–594
- Saynisch, M. (2010) Mastering complexity and changes in projects, economy, and society via second order project management (PM-2), *Project Management Journal* 41(5), pp4–20
- Schwaninger, M. (2009a) Complex versus complicated: The how of coping with complexity, *Kybernetes* 38(1/2), pp83–92, <http://dx.doi.org/10.1108/03684920910930286>
- Schwaninger, M. (2009b) *Intelligent organizations: Powerful models for systemic management*, Springer, ISBN 978-3-540851615
- Schwenke, M., Groesser, S. (2014) *Modellbasiertes Management für dynamische Problemstellungen*, Duncker & Humblot, Berlin, pp139–150
- Senge, P. (1990) *The fifth discipline: The art and practice of the learning organisation*, ISBN 978-05-53456-34-9, Crown Publishing Group, New York, USA
- Senge, P., Sterman, J.D. (1992) Systems thinking and organizational learning, *European Journal of Operational Research* 59(1), pp137–150
- SI Ocean (2013a) Ocean energy technology: Gaps and barriers, <http://si-ocean.eu> [30/05/2014]
- SI Ocean (2013b) Ocean energy: State of the art, <http://si-ocean.eu> [30/05/2014]
- SI Ocean (2014) Wave and tidal energy market deployment strategy for Europe, <http://si-ocean.eu> [19/06/2015]
- SI Ocean (2015) The future of the ocean economy: Exploring the prospects for emerging ocean industries to 2030, <http://si-ocean.eu> [14/08/2015]
- Siemens (2014) Siemens says tidal sector too “niche”: MCT put on selling block, [www.tidaltoday.com](http://www.tidaltoday.com) [26/11/2014]
- Sjöö, K. (2008) The influence of uncertainty on venture capital investments in renewable energy technology: An exploratory study, University of Oslo, Norway, [www.duo.uio.no/handle/10852/17873](http://www.duo.uio.no/handle/10852/17873) [06/05/2014]
- Smit, T., Junginger, M., Smits, R. (2007) Technological learning in offshore wind energy: Different roles of the government, *Energy Policy* 35, pp6431–6444

- Snowden, D. (2002) Complex acts of knowing: Paradox and descriptive self-awareness, *Journal of Knowledge Management* 6(2), pp100–111
- Söderlund, J. (2010) Knowledge entrainment and project management: The case of large-scale transformation projects, *International Journal of Project Management* 28, pp130–141
- Steinhilber, S., Wells, P., Thankappan, S. (2013) Socio-technical inertia: Understanding the barriers to electric vehicles, *Energy Policy* 60, pp531–539
- Sterman, J.D. (1989) Modelling managerial behaviour, *Organizational Behavior and Human Decision Processes* 43(3), pp301–335
- Sterman, J.D. (1992) System dynamics modelling for project management, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, USA
- Sterman, J.D. (1994) Learning in and about complex systems, *System Dynamics Review* 10(2-3), pp291–330
- Sterman, J.D. (2000) Business dynamics: Systems thinking and modeling for a complex world, ISBN: 978-0-0723-8915-9, McGraw-Hill Education
- System dynamics modelling: Tools for learning in a complex world, *California Management Review* 43(4)
- Sterman, J.D. (2001) System dynamics modeling: Tools for learning in a complex world, *California Management Review* 43(4)
- Sterman, J.D. (2002) Systems thinking and modelling for a complex world, Working Paper Series, Engineering Systems Division - Internal Symposium (ESD-WP-2003-01.13-ESD), Sloan School of Management, Massachusetts Institute of Technology, Cambridge, USA
- Sterman, J.D. (2010) Does formal system dynamics training improve people's understanding of accumulation? *System Dynamics Review* 26(4), pp316–334
- Sterman, J.D., Booth Sweeney, L. (2002) Cloudy skies: Assessing public understanding of global warming, *System Dynamics Review* 18(2), pp207–240
- Stiles, J. (1995) Collaboration for competitive advantage: The changing world of alliances and partnerships, *Long Range Planning* 28(5), pp109–112
- Sun, R., Zhang, X. (2004) Top-down versus bottom-up learning in cognitive skill acquisition, *Cognitive Systems Research* 5, pp63–89
- Sutton, J., Austin, Z. (2015) Qualitative Research: Data Collection, Analysis and Management, *The Canadian Journal of Hospital Pharmacy* 68(3), pp226–231
- Swinth, R.L. (1971) Organizational joint problem-solving, *Management Science* 18(2), pp68–79
- Talke, K. (2005) Einführung von Innovationen: Marktorientierte strategische und operative Aktivitäten als kritische Erfolgsfaktoren, ISBN 978-3-8350-0069-8
- Tavner, P.J., Xiang, J.P., Spinato F. (2007) Reliability analysis for wind turbines, *Wind Energy*, Vol. 10(1), pp1–18

- Teece, D.J. (1986) Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy, *Research Policy* 15(6), pp285–305
- Tethys (2018) Sound of Islay Demonstration Tidal Array, <https://tethys.pnnl.gov/annex-iv-sites/sound-islay-demonstration-tidal-array> [21/05/2018]
- Tenders Worldwide (2010) Supplement to the official journal of the EU, <http://ted.europa.eu/TED> [26/10/2010]
- Tesla (2014) All our patents belong to you, [www.teslamotors.com](http://www.teslamotors.com) [07/01/2015]
- Trotter, R., Schensul, J. (1998) Methods in applied anthropology, *Handbook of methods in cultural anthropology*, pp691–736, Walnut Creek, CA
- Toyota (2015) Toyota to give away fuel-cell patents to boost industry, *Agence France Presse*, [www.businessinsider.com](http://www.businessinsider.com) [06/01/2015]
- Transparency Market Research (2016) Wave and tidal energy market: Global industry analysis, size, share, growth and forecast 2016 – 2024, <https://www.transparencymarketresearch.com/wave-tidal-energy-market.html> [17/10/2017]
- Uba, K. (2010) Who formulates renewable-energy policy? A Swedish example, *Energy Policy* 38, pp6674–6683
- UK Energy Research Centre (2012) Technology and Policy Assessment Cost Methodologies Project: Offshore Wind Case Study Working Paper, REF UKERC/WP/TPA/2013/007, Imperial College Centre for Energy Policy and Technology
- Van Dyck, C., Frese, M., Baer, M., Sonnentag, S. (2005) Organisational error management culture and its impact on performance, *Journal of Applied Psychology* 90(6), pp1228–1240
- Vantoch-Wood, A., Connor, P.M. (2013) Using network analysis to understand public policy for wave energy, *Energy Policy* 62, pp676–685
- Veigas, M., Carballoa, R., Iglesias, G. (2014) Wave and offshore wind energy on an island, *Energy for Sustainable Development* 22, pp57–65
- Voith Siemens Hydro (2007) Press release: Voith Siemens Hydro's ocean energies take a big step forward, [www.voith.de](http://www.voith.de) [25/01/2008]
- Wave Energy Scotland (2014) Fact sheet, <http://www.gov.scot/Resource/0046/00464410.pdf> [02/10/2017]
- Wave Energy Scotland (2017) Technology project award, <http://www.waveenergyscotland.co.uk/news-events> [04/10/2017]
- Weber, S. (2005) *The success of open source*, Harvard University Press, ISBN 978-0-6740-1858-7, Cambridge, MA, USA
- Westwood, A. (2005) Offshore wind: Project delays, *Refocus* 09/10, Elsevier Ltd. 1471 0846/05
- Whitesides, G.M., Ismagilov, R.F. (1999) Complexity in chemistry, *Science* 284 (105), pp89–92



- Winkel, M., Radcliffe, J., Skea, J., Wang, X. (2014) Remaking the UK's energy technology innovation system, *Energy Policy* 68, pp591–602
- Wilson, C. (2013) Interview techniques for Ux practitioners, Elsevier Ltd., <http://dx.doi.org/10.1016/B978-0-12-410393-1.00002-8>
- World Energy Council (2016) World energy resources: Marine energy, [https://www.worldenergy.org/wp-content/uploads/2017/03/\[11/10/2017\]](https://www.worldenergy.org/wp-content/uploads/2017/03/[11/10/2017])
- Wu, J.-H., Huang, Y.-L., Liu, C.-C. (2011) Effect of floating pricing policy: An application of system dynamics on oil market after liberalisation, *Energy Policy* 39, pp4235–4252
- Wüstenhagen, R., Menichetti, E. (2012) Strategic choices for renewable energy investment, *Energy Policy* 40, pp1–10
- Wyatt, S. (2014) Financing marine energy: The role of innovation in reducing risk, 5<sup>th</sup> International Conference on Ocean Energy, Canada
- Yasarcan, H. (2013) Simulation modelling to improve decision-making in complex-dynamic environments, Boğaziçi University, Istanbul, Turkey
- Yim, N.-H., Kim, S.-H., Kim, H.-W., Kwahk, K.-Y. (2004) Knowledge-based decision-making on higher-level strategic concerns: System dynamics approach, *Expert Systems with Applications* 27, pp143–158
- Yng Ling, F.Y., Meng Poh, B.H. (2008) Problems encountered by owners of design-build projects in Singapore, *International Journal of Project Management* 26, pp164–173, <http://dx.doi.org/10.1016/j.ijproman.2007.04.001>
- Yoshino, M.Y., Rangan, U.S. (1995) Strategic alliances: An entrepreneurial approach to globalization, Harvard Business School Press, Boston, USA
- Zanuttigh, B., Angelelli, E., Kortenhaus, A., Koca, K., Krontira, Y., Koundouri, P. (2016) A methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting, *Renewable Energy* 85, pp1271–1289
- Zhang, J., Frazier, G.V. (2011) Strategic alliance via co-opetition: Supply chain partnership with a competitor, *Decision Support Systems* 51, pp853–86
- Zhou, Z., Benbouzid, M., Charpentier, J.F., Sculler, F., Tang, T. (2017) Developments in large marine current turbine technologies – A review, *Renewable and Sustainable Energy Reviews* 71, pp852–858

## APPENDICES

## **A      Project plan**

Inspired by the remarkable success of the wind power industry, positive expectations prevail in the marine energy sector to rapidly advance from prototype testing to commercial project implementations. According to EU planning, the grid integration of large-scale tidal current and wave power generation is expected around 2020.

The management of such pioneering and capital-intensive projects requires broad knowledge about the dynamic market behaviour and a realistic sense for the achievable goal. Because of the non-existence of reference projects, innovative assessment tools and management methods are required to provide the necessary security for investment.

Generally marine power projects are exposed to significant risks originating from the combination of applying innovative technology and the need for deliberate deployment in a harsh environment. The implementation of a several-hundred-megawatt scheme represents a major challenge incorporating economic and technological risks. Considering total project life cycle times in the range of decades, covering the period from the feasibility study up to the final decommissioning, strong and long-term commitments of the key parties involved are indispensable.

To improve the probability towards an effective and successful project realisation, a reliable and robust project risk management system must be implemented as a key element of the strategic planning. Sensitive risk identification, in-depth risk analysis and appropriate risk management are indispensable. The impact of risks on the project time schedule and the probability of their occurrence need to be assessed in early stages in order to set up projects realistically, and to be in the position to respond by appropriate measures in a timely manner. By addressing risks methodically, the probability of completing a project to schedule and within budget increases significantly. The focus of the risk management strategy will be continuously on the target factors: cost, time, and quality.

Because of the emerging nature of the tide and wave power sector, guidance must be taken from neighbouring or complementary technology areas such as on-/offshore wind or even modern power grid concepts. In the offshore wind sector, it can be seen that the composition of project developers, the number of manufacturing companies and the ownership structure is less diverse in comparison with the initial onshore project realisations. The reason for the dominance of large utilities and financially strong players in the offshore sector can be found in the higher grade of risk to manage coupled with the significant investment requirement. Contrary to the wind energy sector, marine power technology principally cannot rapidly evolve organically by installing thousands of turbines under favourable onshore conditions. Here the technology maturation and concept selection process will have to be realised within shorter periods and under the proposition of greater evolutionary advancement and under significant qualitative progress. The effective management of complex duties of this type require clever strategies and innovative tools.

The aim and objective of the 6 years part time PhD is to generate fact-based knowledge on key risk complexes and to develop optimised management strategies to accelerate tidal current and wave power project implementations. The methodical analyses will be supported by a system dynamics approach by which knowledge on internal characteristics of decisive cause-effect-relationships will be elucidated. The necessary expert information input will be achieved by identifying the key characteristics in comparable projects, which then serves as the basis for an iterative surveying/interview process. The thesis will identify a systematic approach applying state-of-the-art know-how and developing best-possible solutions thereof in order to ensure project realisations within time, budget and under good reputation.

## **Description of the main working phases**

### **I. Accelerating marine energy development by integration of technology maturation process into utility-scale projects**

The platform for the assessment of the present status of the marine energy sector will be formed by the available literature and the analysis of the development processes in comparable power technology sectors. Hereto especially the evolution and the prospects of the on- and offshore wind industry will be examined concentrating on the situation expected around the year 2020. Generally, the focus will be on the analysis and development of concepts to accelerate marine energy project implementations. The relationship between the technology maturation and the corresponding costs will be examined as well as the consequence on project implementations assessed.

II. First stage survey: Identification of key project characteristics and risk areas retarding project implementations

A standardised approach (e.g. by questionnaires or interviews) will be developed by which selected market participants (policy makers, government bodies, financing institutions, utilities, project developers, consultants, and manufacturers) will be contacted in order to identify experienced or expected risk areas hindering timely commercial-scale device deployments. By identifying the neuralgic facets (e.g. specific technological, organisational or economic circumstances) with the potential to put a project on risk, critical cause-effect-relationships will be diagrammed. By the statistical compression of the information received, conflict areas that require precise investigation will be identified.

III. Second stage survey: Verification of risk complexes and detailing of cause-effect-relationships

The knowledge created in the course of the analysis of the information gained during working phase II will be verified and deepened. Further stakeholder engagement (e.g. targeted interviews) elucidating the essential risk complexes and the outcome of system dynamics simulations will be created. The aim of the in-depth interaction will be to investigate the nature of the identified difficulties in accelerating device deployments and how to limit inherent risks. The feedback loops investigated during this stage will be dynamically modelled and verified using system dynamics software.

IV. Analysis of statistical similarities, key conflict areas, archetype cause-effect networks

Problem-specific abstract representation models will be created based on which parameter variations and alternative scenario studies will be undertaken in order to stabilise the overall project performance. In case of interest in specific investigations by any interviewing partner, such requests can be following if in the interest of the thesis.

V. Detail modelling of risk situations and recommendations to streamline the project implementation progress

The developed simulation models will be completed by sub-routines and calibrated with real-world data. Sensitivity analysis and testing of special-interest feedback loops will be performed. The overall strategy will focus on achieving risk reduction effects to streamline the project performance.

VI. Final clarifications and recommendations for optimised strategic project risk management

A summary outlining the strategies and recommendations for accelerated project implementations will be presented.

In the course of the development of the thesis, it is planned to prepare individual scientific papers for phases I to V.

The thesis is intended to develop confidence towards large-scale project implementations combining the immense experience of today's power industry and the prospects of strategic risk management methods. Knowing the internal behaviour of complex cause-effect-networks will lead to improved decision-making in order to allocate capital and resources efficiently.

Additional information as requested in the 'Handbook for Postgraduate Research Students' (School of Engineering)

- *No specific literature was found on the issue of risk management for tidal current and wave power projects;*
- *Specific resources will not be required, as the information will mainly be received by literature search and contact to market players. For the software modelling, the licenses will be purchased by the candidate;*
- *Apart from the contact with the market players, no further internal or external collaboration is foreseen, other than potential alignment with evolving UKERC activities;*
- *As anticipated deliveries essential cause-effect-relationship diagrams will be provided in software format;*
- *The diagrammatic work plan (estimation of timescales associated with each objective) is attached.*

**B            Background document and questionnaire**

**B.1        Background document**

## 1 Introduction

In contrast to offshore wind, tidal current and wave power technology does not benefit by extension from reliable onshore devices. In order to prepare for the implementation of full-scale commercial projects, the identification and analysis of decisive risk complexes slowing down the progress is required.

With the intention to gain a wide-ranging understanding of the characteristics and difficulties in presently on-going and planned marine energy project activities, interviews with experts from all stakeholder groups are foreseen. With the information gained, inter-organisational blockages and stereotype risk mechanisms shall be identified and analysed in order to streamline the way towards full-commercial power generation by marine energy.

The interviews are part of a PhD study at the Institute for Energy Systems, University of Edinburgh, supervised by:

1<sup>st</sup> supervisor: **Prof Ian Bryden**

Telephone: +44 (0) 131 650 5598, e-mail: [Ian.Bryden@ed.ac.uk](mailto:Ian.Bryden@ed.ac.uk)

2<sup>nd</sup> supervisor: **Dr Scott J Couch**

Telephone: +44 (0) 131 651 3575, e-mail: [Scott.Couch@ed.ac.uk](mailto:Scott.Couch@ed.ac.uk)

**The estimated time requirement for a personal or telephone interview is 20 to 30 minutes.**

## 2 Objective of the research

The joint interest of all parties interacting in marine energy projects is to implement a reliable, cost-effective and environmentally sound power generation system. With the objective to support the development of the sector, the present research specially focusses on:

- the system causality for reaching the target 'full-commercial power generation by marine energy', and
- critical interfaces in the course of the interaction between all stakeholder groups

with the aim to:

- understand underlying interdependencies in the form of critical 'cause-effect-relationships', and
- minimise the impact of stereotype risk mechanisms.

Reported singular-case problems are analysed and contrasted in order to identify limiting universal constellations. Subsequently computer-based system modelling will be applied to master the complexity and to identify scenarios with realistic improvement potential. The overall intention of the research study is to support the effective implementation of utility-scale marine energy projects within time, budget and under acceptable risk.

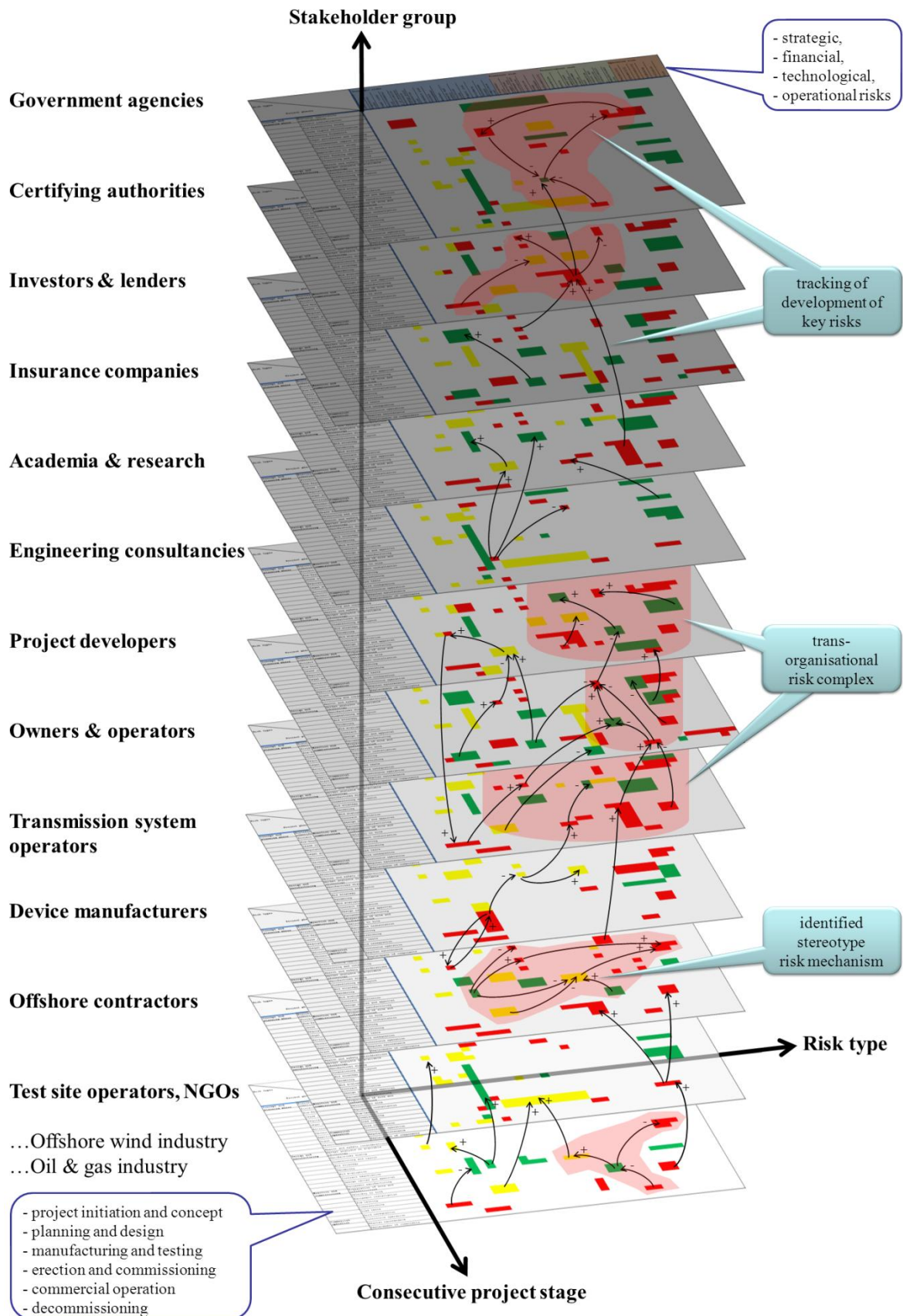
## 3 Holistic approach

Away from stakeholder-internal risk assessment routines focussing on defined criteria (e.g. cost, staffing, technology), in the present study an all-encompassing approach is applied. In such a cross-category environment, the interviewing process has an open-integrative rather than a detailed-specialist character.

The nature of this interdisciplinary research is represented in the 3-d figure on the next page. Each layer represents an averaged risk chart of one stakeholder group in which individually weighted risks are related to project stages. By superimposing multiple risk layers, cross-cutting themes and hidden interdependencies become visible. Of special interest are areas interfacing between (or spanning over) risk owners and transition periods between project stages.

An example for a 'trans-organisational risk complex' is the immediate responsibility for the economic viability of a project – mainly defined by the total investment and the electricity generation capability. This responsibility is variously transferred in the course of the project development and adapted in its accurateness and quality. The comprehensive examination and de-risking of such processes shall help to accelerate the commercialisation of marine energy.

#### 4 Trans-organisational risk layer system



Significant potential for optimisation is expected at: (i) transition periods, (ii) areas of unclear risk ownership, and (iii) the interfaces between contractually defined scopes and responsibilities.



**B            Background document and questionnaire**

**B.2        Questionnaire**

## 1 Calibrating the research study: defining the target project characteristics

*Note: This paragraph serves to direct the research. Multiple selections are possible.*

### 1.1 When do you expect utility-scale electricity generation by marine energy to be a common concept?

Tidal current

☐ before 2015      ☐ 2015 – 2020      ☐ 2020 – 2025      ☐ 2025 – 2030      ☐ after 2030

Wave power

☐ before 2015      ☐ 2015 – 2020      ☐ 2020 – 2025      ☐ 2025 – 2030      ☐ after 2030

### 1.2 Which average farm rating would you expect for the above selected time periods?

Tidal current

☐ < 10 MW      ☐ 10 – 20 MW      ☐ 20 – 50 MW      ☐ 50 – 100 MW      ☐ > 100 MW

Wave power

☐ < 10 MW      ☐ 10 – 20 MW      ☐ 20 – 50 MW      ☐ 50 – 100 MW      ☐ > 100 MW

### 1.3 What average total investment per project would you expect for above defined marine energy farms?

Tidal current

☐ < 10 m€      ☐ 10 – 50 m€      ☐ 50 – 100 m€      ☐ 100 – 200 m€      ☐ > 200 m€

Wave power

☐ < 10 m€      ☐ 10 – 50 m€      ☐ 50 – 100 m€      ☐ 100 – 200 m€      ☐ > 200 m€

## 2 Knowledge transfer and learning from neighbouring sectors

*Note: The focus of the study is on implementing marine energy projects within time, budget and acceptable risk.*

### 2.1 Which are the most valuable experiences gained by the 'early movers' in the marine energy sector?

--	--	--

### 2.2 Which lessons learnt in the offshore wind industry can be transferred to marine energy?

--	--	--

### 2.3 Which lessons learnt in the oil&gas industry can be transferred to marine energy?

--	--	--

### 2.4 Knowledge from which other sectors might be useful to achieve full commercialisation?

--	--	--

### 2.5 Interaction and information interchange with other stakeholder groups

#### 2.5.1 Input information from which stakeholder groups is of key relevance for the work of your organisation?

--	--	--	--

Do you consider the 'input information' you receive as adequately precise/consistent?

☐ Yes ☐ No

#### 2.5.2 Output information: Which stakeholder groups directly use the results/outcome of your organisation's work?

--	--	--	--

Does feedback you receive show that your 'output information' can be directly used/processed? ☐ Yes ☐ No

### 3 Achievements and planning

#### 3.1 Achievements: reflecting the past 2 years

3.1.1 Which were the main achievements of your organisation for the development of marine energy?

--	--	--

3.1.2 Which internal targets appeared more difficult to reach than originally planned?

--	--	--

3.1.3 The initiatives or activities of which stakeholders do you consider as key for the achieved progress?

Stakeholder:

--	--

Initiative or activity:

--	--

3.1.4 What do you consider as main reasons why the marine energy sector has not develop more rapidly?

--	--	--

#### 3.2 Planning: outlook on the next 2 years

3.2.1 Which are top-priority tasks in the work of your organisation to reach full commercialisation of marine energy?

	Task 1	Task 2	Task 3
Your organisation			

3.2.2 Which should be top-priority tasks in the work the other stakeholder groups to reach full commercialisation?

Government agencies			
Certifying authorities			
Investors & lenders			
Insurance companies			
Academia & research			
Eng. consultancies			
Project developers			
Owners & operators			
Transm. sys. operators			
Device manufacturers			
Offshore contractors			
Test site operators			
NGOs			

3.2.3 What measures can be taken to attract more large companies to become involved in marine energy?

--	--	--

*Reference: J. Markard presented in 2009 hypotheses on future investors in offshore wind energy: (i) big companies in the role of project developers and investors; (ii) electric utility companies complementing their conventional power generation portfolio; (iii) firms from the oil&gas industry providing far-reaching competences and able to bear considerable risks [The offshore trend: Structural changes in the wind power sector, Energy Policy 37]. Because of the similarities between marine energy and offshore wind, it is likely that comparable ownership structures will develop.*

3.2.4 In which areas is research most required to accelerate the development of marine energy?

--	--	--

## 4 Cost aspects

### 4.1 Where do you see the greatest concerns for delays and cost-overruns in marine energy projects?

--	--	--

### 4.2 Where do you see significant potential to get the cost for utility-scale project implementations down?

--	--	--

### 4.3 What are the main factors driving up the insurance cost?

--	--	--

### 4.4 What measures can be taken in marine energy to avoid experienced cost increase in offshore wind?

*Reference: According to the UKERC 2010 report 'Great Expectations: the cost of offshore wind in UK waters' the main causes for the dramatic cost increases from 2005 to 2009 were: (i) complexity of the planning process; (ii) particular supply chain bottlenecks; (iii) escalations associated with making offshore turbines reliable.*

Measure(s) to reduce the 'complexity of the planning process':

--	--	--

Measure(s) to reduce 'supply chain bottlenecks':

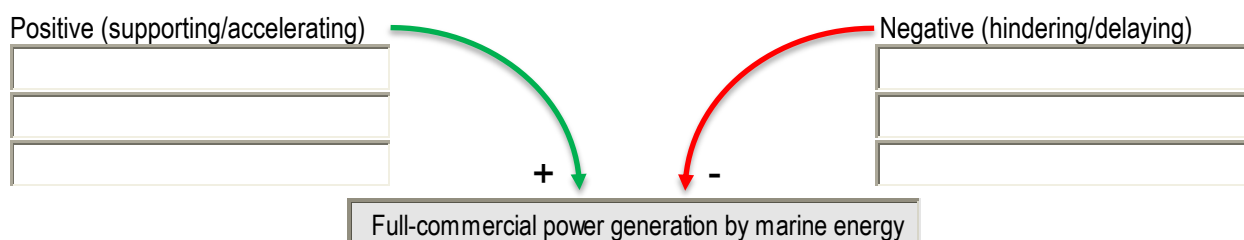
--	--	--

Measure(s) to increase the 'equipment reliability':

--	--	--

## 5 Main impact factors on reaching the target 'full-commercial marine energy'

*Note: Please think about qualitative, top-level, decisive influence factors (e.g. political support, environment, energy).*



## 6 Risks

### 6.1 Which are the key risks in commercial-scale marine energy per project phase?

Project initiation and concept: ---  
 Planning and design: ---  
 Manufacturing and testing: ---  
 Erection and commissioning: ---  
 Commercial operation: ---  
 Decommissioning: ---

### 6.2 Risk transfer or risk propagation

*Reference: As the electricity generation capacity (GWh per year) represents one of the key characteristics of each power project, the factors determining this value are of key relevance. In the course of a marine energy project, the responsibility for the electricity generation capacity experiences several step changes concerning the 'risk ownership' and the 'quality of information': e.g. from the study/concept phase (consultancy) to the equipment manufacturer.*

Which 'risk transfer' or 'risk propagation' processes do you expect during a complete marine energy project life cycle?

--	--	--


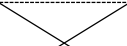
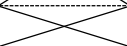
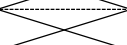
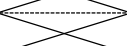


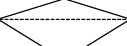
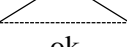
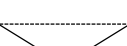

### 6.3 Please correlate each risk type to an estimated risk level

		Risk level low	Risk level medium	Risk level high
Strategic risks	<b>Regulatory issues</b>			
	- Obtaining sea use license	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Obtaining license to construct	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Obtaining permit for grid connection	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Environmental impact</b>			
	- Impact on marine flora/fauna	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Shoreline evolution/sediments	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Public perception	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Accidents	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Conflicts of use</b>			
	- Professional fishery	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Offshore wind	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Military	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Leisure activities	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Infrastructure and logistics</b>			
	- Capability of shipyards/ports/vessels	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Access to skilled workforce	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
- Supply-chain constraints	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
<b>Project management</b>				
- Keeping time schedule	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
- Keeping budget	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Financial risks	<b>Funding requirement</b>			
	- Achieving funding	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Profitability requirement</b>			
	- Appropriateness of feed-in tariff	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Market development risk	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Achievement of energy yield data	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Insurance requirement</b>			
- Acceptable insurance cost	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
- Acceptable coverage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Technological risks	<b>Ambient requirements</b>			
	- Ground conditions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Extreme weather situations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Energy conversion system</b>			
	- Manufacturability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Installability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Maturity	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Interfaces	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Mooring	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<b>Power export</b>			
- Inner-park cabling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
- Grid interface	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
- Regional grid capability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Operational risks	- Reliability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Operability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Survivability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Maintainability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Training of staff	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Grid stability requirements	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Accidents	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	- Health and safety	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Your recommendation: \_ \_ \_

**C        Expert interviews**

**C.1      List of participants**

#	(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	
01 Government (associations) & trade organisation					
1	The Scottish Government, UK <i>Programme Manager Low Carbon Infrastructure</i>	1			ok
2	Marine Scotland, UK <i>Marine Spatial Planning Theme Leader</i>	1			ok
3	Energy Technologies Institute, Ireland <i>Strategy Manager</i>	1			ok
4	The Carbon Trust, UK <i>Charlie Blair, Technology Acceleration Manager</i>			1	ok
5	Department of Energy and Climate Change, UK <i>Head of the Wave &amp; Tidal Team</i>			1	ok
6	The Crown Estate <i>Programme Manager (Wave &amp; Tidal)</i>			1	ok
7	Scottish Natural Heritage <i>Marine Renewables Research and Guidance</i>		1		ok
8	Natural England				
9	Centre for Environment, Fisheries & Aquaculture Science <i>Programme Director for Marine Renewables</i>		1		ok
10	Joint Nature Conservation Committee <i>Programme Leader</i>				
11	Forum for Renewable Energy Development in Scotland				
12	Marine Energy Group (MEG)				
13	Renewables Advisory Board (RAB)				
14	Department of Trade and Industry (DTI)				
15	Nova Scotia				
16	RenewableUK <i>Wave and Tidal Energy Development Manager</i>			1	ok
17	Welsh Government <i>Energy Advisor to the Welsh Government</i>				
18	European Commission - Maritime Affairs and Fisheries				
19	Scottish European Green Energy Centre				
20	EU Ocean Energy Association <i>Principal Administrator</i>				
21	Technology Strategy Board (TSB) <i>Head of Energy</i>		1		ok
22	Sustainable Energy Authority of Ireland (SEAI) <i>Head of Department</i>				

#		Type of Feedback			Total
		(1) Questionnaire	(2) Telephone interview	(3) Personal interview	
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	44
<b>02 Certifying authorities</b>					
1	Det Norske Veritas BV (DNV) <i>Senior Principal Surveyor</i>			1	ok
2	Germanischer Lloyd <i>Head of Department R&amp;D, Renewables Certification</i>				
3	Lloyd's Register Group Services Ltd. <i>Global Technology Leader Renewable Energy</i>	1			ok
4	American Bureau of Shipping (ABS) <i>Director</i>				
<b>03 Investors &amp; lenders</b>					
1	Scottish Development International <i>Head - Energy, Trade and Investment</i>				
2	European Investment Bank <i>Senior Loan Officer</i>				
3	Capital Partners Worldwide				
4	Green Giraffe <i>Founding Partner &amp; President</i>	1			ok
5	PricewaterhouseCoopers <i>Partner</i>				
<b>04 Insurance companies &amp; law firm</b>					
1	GCube Underwriting Ltd. <i>Underwriter</i>				
2	Arthur Cox <i>Partner</i>				
3	Philip Lee Solicitors <i>Environment and Planning Partner</i>				
4	Eversheds International <i>Partner</i>		1		ok
5	Lawrence Graham <i>Partner</i>				
<b>05 Academia &amp; research</b>					
1	University of Washington <i>Research Assistant Professor</i>	1			ok
2	Exeter University <i>Lead academic</i>				
3	Manchester University <i>Head of School, Professor of Hydrodynamics</i>				
4	Queens University Belfast <i>Professor of Coastal Engineering</i>				
5	University of Edinburgh, 1 <sup>st</sup> interviewee <i>Professor, Head of the Institute for Energy Systems</i>			1	ok
6	University of Edinburgh, 2 <sup>nd</sup> interviewee <i>Senior Research Fellow</i>			1	ok



#	(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	
02 Certifying authorities					
7	University of Stuttgart <i>Deputy Director Institute of Fluid Mechanics</i>				
8	Fraunhofer IWES <i>Head of Marine Energy</i>				
9	Aalborg University <i>PhD Student</i>				
10	University of Oxford <i>Associate Professor in the Department of Engineering Science</i>				
11	National Taiwan Ocean University <i>Professor for Harbor and River Engineering</i>	1			ok
12	University of Massachusetts-Dartmouth <i>Programme Manager</i>				
13	University College Cork <i>Offshore Renewable Energy Research Engineer</i>				
14	Ifremer				
15	Pacific Northwest National Laboratory <i>Senior Manager</i>				
16	Irish Marine Institute <i>Section Manager Oceanographic Services</i>	1			ok
17	Oak Ridge National Laboratory <i>Water Resources Engineer</i>				
18	Idmec				
06 Engineering consultancies					
1	Garrad Hassan <i>Head of Tidal Energy</i>				
2	Natural Power <i>Marine Renewables Engineer</i>	1			ok
3	Aquatera <i>Managing Director</i>				
4	SgurrEnergy <i>Associate Director</i>				
5	Astrimar Ltd. Chartered Engineer				
6	Xodus Group Ltd. <i>Principal Engineer</i>	1			ok
7	TecNALIA Research & Innovation <i>Vice-Chair</i>	1			ok
8	South West Renewable Energy Agency <i>Programme Director</i>		1		ok
9	Black and Veatch <i>Senior Renewable Energy Consultant</i>				
10	Royal Haskoning <i>Technical Director for Wave and Tidal</i>			1	ok

#	(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	
11	RE Vision Consulting <i>Owner</i>				
12	RPS Consulting Engineers <i>Director</i>				
07 Project developers					
1	EMERA <i>Senior Manager</i>		1		ok
2	RWE Innogy <i>Marine Technology Manager</i>				
3	EDF R&D <i>Marine Energies Project Manager</i>		1		ok
4	Carnegie Wave Energy Ltd. Executive Director – European Business Development				
5	MeyGen Ltd. <i>CEO</i>				
6	Electricity Supply Board (ESB) <i>Manager</i>		1		ok
7	Iberdrola <i>Head of Offshore Renewables</i>		1		ok
8	Scottish Enterprise <i>Project Manager</i>				
08 Owners & operators					
1	ScottishPower Renewables (SPR) <i>Head of Policy</i>			1	ok
2	E.ON Climate & Renewables <i>Marine Energy Manager</i>				
3	Vattenfall <i>Head of low emitting energy research and development</i>				
4	Aegir Wave Power <i>Programme Director</i>				
5	Statkraft <i>Vice President</i>				
6	Ente Vasco de la Energía <i>Project Manager Mutriku Wave Plant</i>			1	ok
09 Transmission system					
1	SSE <i>Marine Engineer</i>	1			ok
2	SmartestEnergy				
3	National Grid <i>Customer Services UK</i>				
4	Friends of the Supergrid				
5	Eirgrid <i>Consultant Engineer</i>				

#	(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	
10 Device manufacturers					
1	Marine Current Turbines <i>Head of Business Development</i>			1	ok
2	Pelamis Wave Power <i>Project Development Manager</i>		1		ok
3	Verdant Power <i>Hydrodynamic Engineer</i>				
4	Voith Hydro Ocean Current Technologies <i>Managing Director</i>				
5	Tidal Generation Limited (Rolls-Royce Group) <i>Project Development Manager</i>				
6	Ocean Power Technologies <i>Managing Director of UK and European Business</i>				
7	Aquamarine Power <i>Head of Commercial Development</i>				
8	AWS Ocean Energy <i>CEO</i>				
9	Hammerfest Strøm UK Ltd.				
10	Open Hydro Tidal Technology <i>Environmental and External Affairs Manager</i>				
11	Lockheed Martin				
12	AW-Energy				
13	Norwegian Ocean Power AS				
14	Oceanlinx				
15	Wavebob Ltd. <i>CEO</i>		1		ok
16	WavePiston APS				
17	Atlantis Resources Corporation <i>Director of Corporate Development</i>				
18	Babcock International Group <i>Engineering Manager Renewables</i>				
19	Siemens <i>Vice President Hydro &amp; Ocean Power</i>	1			ok
20	Wave Star A/S <i>Head of Development</i>	1			ok
21	Ocean Renewable Power Company <i>Project Developer Manager</i>	1			ok
22	Pulse Tidal <i>Chief Technical Officer</i>				
23	ESB International <i>Programme Manager</i>				
24	Minesto <i>Co- Founder and CEO</i>				

#		(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
			Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
			18	15	11	44
25	ABB <i>Group Vice President</i>					
26	ITP <i>Principal Marine Engineer</i>					
27	TidalStream Limited <i>Joint Founder</i>					
28	Scotrenewables Tidal Power Ltd. <i>Managing Director</i>					
29	Sustainable Marine Technologies <i>Managing Director</i>					
30	Bomborawavepower <i>Executive Director</i>					
<b>11 Offshore contractors</b>						
1	Mojo Maritime Ltd. <i>Naval Architect</i>					
2	SBM Offshore					
3	Direction Technique des Constructions Navales (DCNS) <i>Director of Business Development</i>					
4	RES Offshore <i>Director of Corporate Development</i>					
5	Bluewater <i>New Energy Market Developer</i>					
6	Searoc <i>Group's Head of Operations</i>					
<b>12 Test site operators</b>						
1	Wave Hub <i>General Manager</i>					
2	Wave Energy Centre <i>Executive Director</i>					
3	Wave Energy Planning and Marketing <i>Project Coordinator</i>					
4	European Marine Energy Centre (EMEC) <i>Research &amp; Project Coordinator</i>		1			ok
5	Fundy Ocean Research Centre for Energy (FORCE) <i>Communications Director</i>			1		ok
6	National Renewable Energy Centre (narec) <i>Key Account Manager</i>			1		ok
7	Minas Basin Pulp and Power <i>Vice President Energy Department</i>		1			ok
8	France Energies Marines <i>Test Site Coordinator</i>			1		ok

#	(1) Questionnaire (2) Telephone interview (3) Personal interview	Type of Feedback			Total
		Q <sup>(1)</sup>	T <sup>(2)</sup>	P <sup>(3)</sup>	
		18	15	11	
13 NGOs					
1	Greenpeace Chief Scientist		1		ok
2	World Wildlife Fund (WWF)				
3	Climate Bonds Initiative Chair				
14 Offshore wind industry					
1	Siemens AG, Energy Sector				
2	Renewable Energy Technology Center				
3	Vestas Wind Systems				
4	Dong Energy Power (UK) Senior Development Manager	1			ok
15 Oil & gas industry					
1	BP Marine Ltd.				
2	TOTAL S.A.				
3	Royal Dutch Shell				
4	Eni S.p.A.				

- C**      **Expert interviews**
- C.2**    **Respondents per question**

#	Question	Government (...) & trade organisation	Certifying authorities	Investors & lenders	Insurance companies & law firm	Academia & research	Engineering consultancies	Project developers	Owners & operators	Transmission system owners	Device manufacturers	Test site operators	NGOs	Offshore wind industry	Total
<b>1</b>	<b>Calibrating the research study: defining the target project characteristics</b>														
1.1	When do you expect utility-scale generation by marine energy to be a common concept?	8	2	1		3	5	3	2		3	1	1		<b>29</b>
1.2	Which average farm rating would you expect for the above selected time periods?	7	2	1		4	5	3	3		3	1	1		<b>30</b>
1.3	What average total investment per project would you expect for marine energy farms?	7	2	1		6	4	3	2		4	1	1		<b>31</b>
<b>2</b>	<b>Knowledge transfer and learning from neighbouring sectors</b>														
2.1	Which are most valuable experiences gained by 'early movers' in marine energy?	1 0	2	1	1	5	5	4	2	1	6	4			<b>41</b>
2.2	Which lessons learnt in the offshore wind industry can be transferred to marine energy?	1 0	2	1	1	5	4	4	2	1	6	4			<b>40</b>
2.3	Which lessons learnt in the oil&gas industry can be transferred to marine energy?	9	2	1	1	4	4	4	2	1	6	4			<b>38</b>
2.4	Knowledge from which other sectors might be useful to achieve full commercialisation?	9	1	2	2			4	2	1	6	3			<b>30</b>
<b>2.5</b>	<b>Interaction and information interchange with other stakeholder groups</b>														
2.5.1	Input information from which stakeholder groups is of key relevance for the work of your organisation?	9	2		1	2	5	3	2	1	4	3			<b>32</b>
	Do you consider the 'input information' you receive as adequately precise / consistent?	6	1		1	1	5	4	2	1	5		3		<b>29</b>
2.5.2	Output information: Which stakeholder groups directly use results / outcome of your organisation's work?	9	2		1	2	5	3	2	1	4	3			<b>32</b>
2.5.2	Does feedback you receive show that your 'output information' can be directly used / processed?	8	1		1	3	5	3	1	1	3		3		<b>29</b>

#	Question	Government (...) & trade organisation	Certifying authorities	Investors & lenders	Insurance companies & law firm	Academia & research	Engineering consultancies	Project developers	Owners & operators	Transmission system owners	Device manufacturers	Test site operators	NGOs	Offshore wind industry	Total
<b>3</b>	<b>Achievements and planning</b>														
<b>3.1</b>	<b>Achievements: reflecting the past 2 years</b>														
3.1.1	Which were the main achievements of your organisation for the development of marine energy?	9	1			1	5	3	2		4	2			<b>27</b>
3.1.2	Which internal targets appeared more difficult to reach than originally planned?	7				1	3	3	2		2	1			<b>19</b>
3.1.3	The initiatives or activities of which stakeholders do you consider as key for the achieved progress?	8	1			2	4	3	2		3	1			<b>24</b>
3.1.4	What do you consider as main reasons why the marine energy sector has not develop more rapidly?	8	2	1		3	5	2	2		3	1			<b>27</b>
<b>3.2</b>	<b>Planning: outlook on the next 2 years</b>														
3.2.1	Which are top-priority tasks in the work of your organisation to reach full commercialisation of marine energy?	8	2	1		1	4	2	2		3	1	1	1	<b>26</b>
3.2.2	Which should be top-priority tasks in the work of other stakeholder groups to reach full commercialisation?	6	2	1		1	5	3	2		3	1	1		<b>24</b>
3.2.3	What measures can be taken to attract more large companies to become involved?	8	2	1		1	5	3	2		3		1		<b>26</b>
3.2.4	In which areas is research most required to accelerate the development of marine energy?	9	2			5	5	2	2		5	2			<b>32</b>

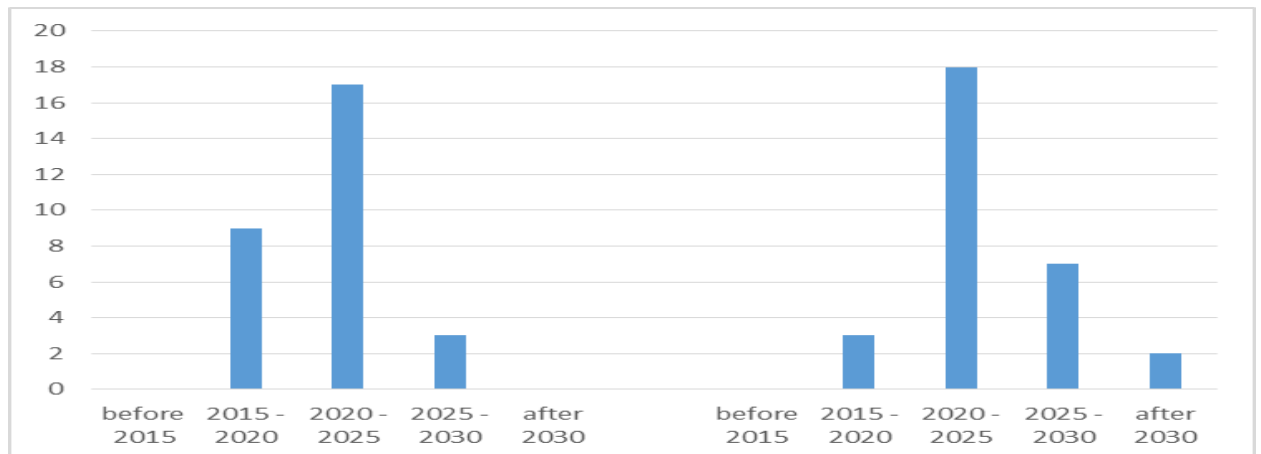


#	Question	Government (...) & trade organisation	Certifying authorities	Investors & lenders	Insurance companies & law firm	Academia & research	Engineering consultancies	Project developers	Owners & operators	Transmission system owners	Device manufacturers	Test site operators	NGOs	Offshore wind industry	Total
<b>4</b>	<b>Cost aspects</b>														
4.1	Where do you see greatest concerns for delays & cost-overruns in marine energy projects?	7	2	1	1	4	4	3	2	1	5	4			<b>34</b>
4.2	Where do you see significant potential to get cost for utility-scale implementations down?	7	2	1	1	4	3	3	2	1	5	3			<b>32</b>
4.3	What are the main factors driving up the insurance cost?	4	1	1		4	2	2	2		4	1			<b>21</b>
4.4	What measures can be taken to avoid experienced cost increase in offshore wind?	6	1	1		1	3	2	2		2	1			<b>19</b>
<b>5</b>	<b>Main impact factors on reaching the target “full-commercial marine energy”</b>	1 0	2	1	1	5	4	4	2	1	6	5	1		<b>42</b>
<b>6</b>	<b>Risks</b>														
6.1	Which are the key risks in commercial-scale marine energy per project phase?	6	2	1		1	2	2	1		2				<b>17</b>
6.2	Risk transfer or risk propagation	4	1	1			2	1	1		2				<b>12</b>
6.3	Please correlate each risk type to an estimated risk level	1 0	2	1	1	4	4	4	2	1	6	4	1		<b>40</b>

## **D        Primary interview results and statistical findings**

## 1 CALIBRATING THE RESEARCH: TARGET PROJECT CHARACTERISTICS

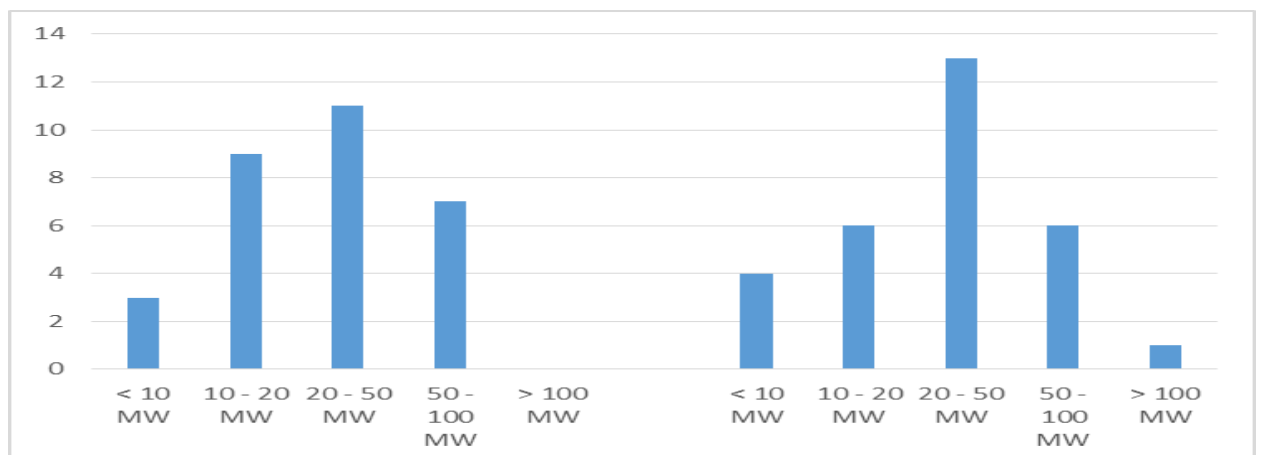
**When do you expect utility-scale electricity generation by marine energy to be a common concept?**



Mean: Tidal current: 2021

Wave power: 2024

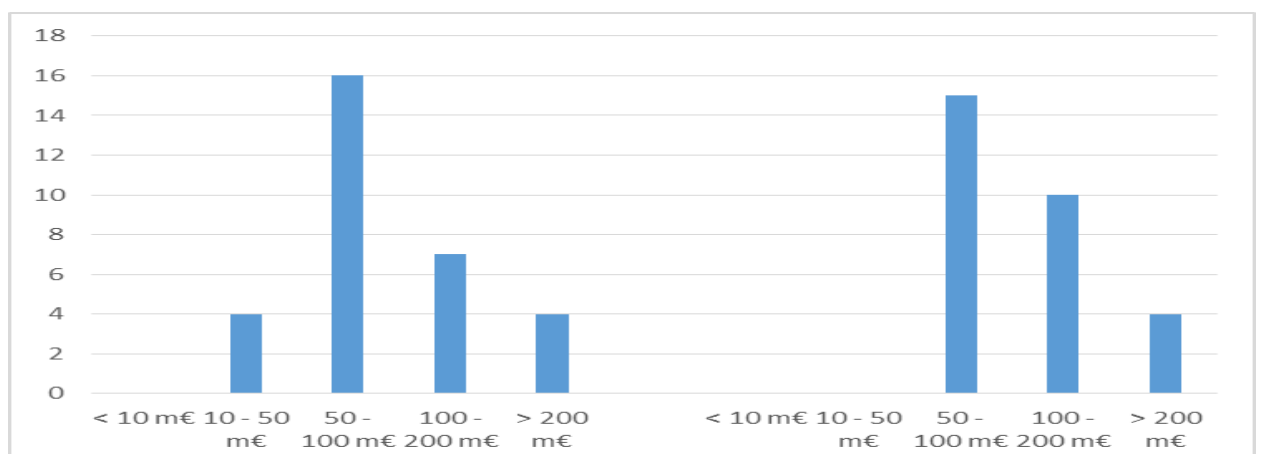
**Which average farm rating would you expect for the above selected time periods?**



Mean: Tidal current: 36 MW

Wave power: 38 MW

**What average total investment per project would you expect for above marine energy farms?**



Mean: Tidal current: 102 m€ (~2,900 €/kW)

Wave power: 118 m€ (~3,100 €/kW)

## 2 KNOWLEDGE TRANSFER AND LEARNING FROM NEIGHBOURING SECTORS

**Which are the most valuable experiences gained by the early movers in the marine energy sector?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
27.1 %	6.3 %	2.1 %	4.2 %	16.7 %	10.4 %	24.0 %	9.4 %

Representative interview statements
<b>Marine operations experience</b> <i>The importance of testing devices in real conditions / Offshore deployment &amp; installation experience / Learn about the difficulties of the marine environment / Effective and cheap installation vessels / Dealing with design challenges in this environment / Acknowledgement of harsh environment that triggers iterative design and build phases / Importance of real site measurements in understanding resource and estimating energy production / Effective installation strategies.</i>
<b>Device operation experience</b> <i>Operation and maintenance experience of asset / Having operational devices in the sea / Performance experience / Efficiency calculation.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Better understanding of the resource / Understand that marine energy is a risky business / Need for transparency, community outreach and support / Mitigation of weather risk / Early site and resource assessment is key.</i>
<b>Project financing</b> <i>Proper financial backing and support / Control of investment capital / Time and cost of developing devices greater than expected / Recognition that cost of electricity is a key driver / Acknowledging of support and financing mechanisms / Benefits in gaining interest of investors / Demonstration of technology (access of funding).</i>
<b>Business development</b> <i>Cornering the market to demonstrate the viability to investors / Engagement with industry and government / Prove of concept (management process) / Missing industrialisation of sector / Early market entry can be critical / Learning about development steps as the sector evolves from an R&amp;D background / Integration of supply chain (building a new industry) / Progress not as expected / Bringing technology to market / Market opportunity.</i>
<b>Reduction of CapEx and OpEx</b> <i>Cost reduction / Proven O&amp;M costs / Spares, spares, spares / Costs are much higher when moving to the sea / Commercial experience / Ability to reduce costs / More expensive than expected / Understand cost of supply (experience of oil &amp; gas) / Incremental advances are much more expensive than originally anticipated.</i>
<b>Technology learning</b> <i>Identification of most efficient sites / Identification of less-conflict-areas / Subsea cable connection / Understanding the behaviour of the technology / Accurate energy yield prediction / Essential design characteristics / Longer baseline for systems reliability / Basic device function / Understanding of resource / Gradual improvement in survivability through testing designs in the marine environment / Reliability more important than efficiency / Design improvements resulting from the lessons learned / Devices have to be design to be installed and maintained (not only operated) / Technology know-how / Technology confidence / Fail in unexpected part of project / Technology development needs to drive site development (and not other way round) / Learning by doing / Things take longer that you would ever have imagined / Failures (refine ideas).</i>
<b>Consenting, leasing, licensing</b> <i>Planning system (complicated and time delaying) / Managing the regulatory system / Access to the best sites / Importance of site control and permitting / The importance of early engagement with regulatory authorities (failure to do so can cause delays with any potential project) / Overriding practical challenges (environment) / Prove of design (ways for consenting) / Environmental monitoring and data.</i>

**Which lessons learnt in the offshore wind industry can be transferred to marine energy?**

Working at sea in hostile conditions	Manage an array full of assets and operate it 24/7	Subsea cabling lay, cable inter-connection, grid interface, network operation	Project structuring, project/risk management and EIA	Health and Safety	Reduction of CapEx and OpEx	Improving reliability	Consenting, leasing, licensing
17.7 %	12.5 %	18.8 %	10.4 %	3.1 %	9.4 %	20.8 %	7.3 %

Representative interview statements
<b>Working at sea in hostile conditions</b> <i>Site survey techniques / Vital to have the infrastructure in place to support the industry (deployment, maintenance of devices) / DP (dynamic positioning) vessel operation / Difference in design, manufacturing and logistics compared to offshore oil &amp; gas / Skills / Access / Installation / Marine operations / Vessel and personnel availability / Vessels and marine navigation / Experience from offshore surveys / Experience by project realisations / Installation processes, landing platform / Ocean floor drilling techniques and equipment / ROV techniques / Installation, planning, project management.</i>
<b>Manage an array full of assets and operate it 24/7</b> <i>Optimised O&amp;M strategies (grouping of interventions) / Electrical infrastructure construction &amp; operations / Guidance to O&amp;M / Logistics of O&amp;M / Aggregation of power in arrays / Challenges around servicing in harsh environments / O&amp;M (i.e. how to access, how to transfer personnel) / Operational support, service, maintenance, repair / Operation and maintenance data / Required and suitable experience / Skillset of labour.</i>
<b>Subsea cabling lay, cable inter-connections, grid interface, network operation</b> <i>Cabling and grid issues / Cable laying / Cabling technology / Broader energy system like network operation / Transfer power from on-/offshore / Cable protection / Power cable and transmission / Power electronics and transformer reliability / Grid issues / Subsea cabling / Offshore electrical infrastructure (substations, cabling) / Subsea power aggregation and transmission / Interconnection of generators / Offshore grid connection / Grid integration and connection.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Environmental impact assessment (EIA) / The sharing of knowledge and lessons learnt to avoid duplication of time and effort / Project structuring / Risk management / Overall framework of development and business terminology / Knowledge sharing need to be better / Contracting risks / Project management / Construction and project management / Contracting approach (EPC) / Project development capital cost / Environmental issues / Offshore transport / Synergies effect by coupling different kind of renewable / Regulation and standards.</i>
<b>Health and Safety</b> <i>HSSE (health, safety, security &amp; environment) requirements &amp; organizational aspects / Marine safety.</i>
<b>Reduction of CapEx and OpEx</b> <i>Process to reduce operating cost (maintenance) / Cost reduction / Cost reduction curve / Finance assessment / Cost control / Project finance / Cost of electricity production dependant on capacity deployed / Cost of failures / Cost of deployment.</i>
<b>Improving reliability</b> <i>Marine technology / Improving reliability / Innovation related to reliability / Design of offshore structure subject to complex loading / Technology transfer / Reliability (or otherwise) of components / Fatigue / Choice of components for harsh conditions e.g. connectors, cables, moving parts / Materials / Monitoring technology / Availability is king / Spending money to increase availability is always worthwhile / Power engineering / Civil works / Support structures (technology) / Range of engineering issues and learning common to both sectors / Building support infrastructure / Design and layout of machines / Mooring / Foundation calculation / Balance of plant / Remote underwater sensing / Value of lessons learnt.</i>
<b>Consenting, leasing, licensing</b> <i>Streamline the process (e.g. grid connection) / Understanding the consenting process / Consent approvals / Consultation and consenting process / Permitting and regulatory aspects / Main barrier is legal barrier (consenting) / Licensing, permitting, consenting, getting access to the project.</i>

**Which lessons learnt in the oil & gas industry can be transferred to marine energy?**

O&M strategies and methods	Oil & gas bespoke technology, one-off solutions	24/7 sub-sea marine operations, installation, deployment, ROVs	Project structuring, project/risk management and EIA	Health and Safety	Reduction of CapEx and OpEx	Marine technology (structural design, mechanical integrity, materials, bio-fouling)	Risk sharing contractually optimised
7.3 %	6.3 %	24.0 %	13.5 %	11.5 %	4.2 %	30.2 %	3.1 %

Representative interview statements
<b>O&amp;M strategies and methods</b> <i>Construction / O&amp;M / managing large projects / Equipment supply and maintenance / Cabling and anchoring design and implementation / Marine operations / Vessel positioning.</i>
<b>Oil &amp; gas bespoke technology, one-off solutions</b> <i>Not many lessons learnt / “Not that much” because oil &amp; gas solutions are too expensive / “Similar problems” as in oil &amp; gas sector have to be solved with lower budget / “Big problems, big money” / Oil &amp; gas is characterised by bespoke, one-off technology / marine energy either series production / Access to platform offshore.</i>
<b>24/7 sub-sea marine operations, installation, deployment, ROVs</b> <i>Sub-sea marine operations / Subsea operations / Knowledge of working in harsh environment / How to use less specialist vessels (cheaper) / Installation / Working in marine systems / Experience with 24/7 operations in marine environment / Manpower and logistics / ROV capabilities / Subsea intervention operations / Challenges around servicing in harsh environments / Access (incl. installation) / Working at sea / Offshore marine operations / Marine operations / Logistics and deployment / Marine infrastructure / Mooring systems, foundation, new materials / How to deploy technology / Installation.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Supply chain / Project structure (system approach) / Project management / Skills / Time to complete tasks / Need to restructuring of supply chain / Project management (lower budget) / Risk management (one marine energy device manufacturers worked with Chevron) / Contracting / Ability to quantify risk on reliable operation.</i>
<b>Health and Safety</b> <i>HSSE requirements &amp; organizational aspects / Health and safety risk / H&amp;S safety best practice.</i>
<b>Reduction of CapEx and OpEx</b> <i>O&amp;M cost reduction / Accept that offshore intervention is expensive and optimise within that constraint.</i>
<b>Marine technology (structural design, mechanical integrity, materials, bio-fouling)</b> <i>Standardisation for components (e.g. cable fittings) / Mechanical integrity / Structural design / Technology (subsea) / “Marinsation” of equipment / Design of equipment for harsh metocean conditions / Materials / Wet-mate power and communications / Opportunities for standardisation / Choice of components for harsh conditions e.g. connectors, cables, moving parts / Corrosion and bio fouling control / Structural engineering standards / Survivability / Substations and cables / Design for reliability &amp; survivability / Redundancy concepts / Installability / Reliability and operability / Connection and disconnection systems (replacement of components) / Submerged structures / Foundation design, geotechnical analysis / Survivability / Cable connection techniques / Corrosion protection / Structured engineering / Extreme engineering / Trenching systems (cable lay) / Logistics.</i>
<b>Risk sharing contractually optimised</b> <i>Very grown up contracting experience / Risk assessment / Model for analysis.</i>

**Knowledge from which other sectors might be useful to achieve full commercialisation?**

Offshore wind or other maritime affairs	Conventional power generation (hydro, thermal, nuclear)	Shipbuilding	Aerospace and defence	Initial marine energy deployments	Aquaculture and environment	Information technology	Serial production industry
12.1 %	37.4 %	6.6 %	9.9 %	11.0 %	3.3 %	6.6 %	13.2 %

**Representative interview statements****Offshore wind or other maritime affairs**

*Offshore wind: consenting process / Port sector: structures for harsh environment / Maritime: low cost supply chain / Marine sector / Maritime sector in general / Sub-sea cabling / Offshore equipment manufacturers / Regulatory environment / Shipping (management, regulation) / Other renewables and business models / Contractual setup / Other renewable sectors or industries / Knowledge from marine fleets and how they hold station in 5.5 m/s tidal flows / Remote sea bed drilling.*

**Conventional power generation (hydro, thermal, nuclear)**

*Basic manufacturing expertise, technologies, supply chain / Materials / Large-scale manufacturing / Utility-end-user requirements, etc. / Nuclear (risk) / Supply chain management / Other renewable sectors / Expertise of large OEMs (e.g. ABB, Siemens) / Engineering problems / Technology confidence / Universities: R&D, material, energy conversion / Insurance companies: transport, insurance for sites, for equipment / Energy storage and/or transmission / Energy companies and distribution: monitoring, maintenance, environment and planning (permits, agreement) / Utilities.*

**Shipbuilding**

*Shipping industry (corrosion management) / Naval fabrication / Maritime industry.*

**Aerospace and defence**

*Aerospace (manufacturing, condition monitoring, system design, etc.) / Defence industry (management of high value assets, maintaining) / Aerospace (probabilistic) / Composites and advanced materials.*

**Initial marine energy deployments**

*How to put in place and develop an effective support infrastructure to ensure the ongoing deployment and maintenance of devices / Learning from initial deployments / Finance / Ways in which to attract investment from developers and corporate bodies / Ways in which to attract, train and retain skilled staff committed to the sector, Environment (assessing impacts) / Much more time required / Project development expertise / Fail in unexpected part of project / Time and cost of developing devices greater than expected / Importance of real site measurements in understanding resource and estimating energy production / Projects and industries with pilot character.*

**Aquaculture and environment**

*Environmental data / Aquaculture (fish) - moorings, regulation.*

**Information technology**

*Any sector developing new technology / Power electronics and conditioning / Communication collaboration (ICT - Information, Communication Technology), networks / RFCD, embedded computing, system engineering.*

**Serial production industry**

*Automotive - scale-up & mass production / Lean manufacturing / Production line manufacturing / Manufacturing: automotive (batch, composite) / Series production / Bringing technology to market / Automobile industry.*

### 3 ACHIEVEMENTS AND PLANNING

**Which were the main achievements of your organisation for the development of marine energy?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
3.0 %	15.0 %	-	11.0 %	35.0 %	-	23.0 %	13.0 %

Representative interview statements
<b>Marine operations experience</b> <i>First arrays in the water / Have Mutriku wave power plant up and running.</i>
<b>Device operation experience</b> <i>Deployment and retrieval of a 1 MW turbine / Full-scale device in the water / Direct access to feedback (important: information about “what it really costs”) / Installed the first, federally licensed, grid connected marine hydrokinetic power - the first project of its kind in all of the Americas.</i>
<b>Project structuring, project/risk management and EIA</b> -
<b>Project financing</b> <i>Funding projects (prototype) / Providing funds for 6 different project developers / 5 ROCs / Funding of about 20 projects (wave and tidal devices) / Shaping up front capital support / PPA under discussion in Maine / Manage the challenges of the high risk business during the global economic crisis / Raise capital.</i>
<b>Business development</b> <i>Commissioning major innovation projects / Concluding long-term innovation projects / Working on the level of revenue support / Putting the UK in the lead of project development / Contributing to DECC Marine Action Plan / Establishment of one stop shop for licensing / Publishing industry performance and cost targets / Starting PhDs in Marine renewables / Development of policy at government level / Creation of a company together with an utility to develop a wave energy converter / Winning contracts from marine energy developers / Production of public resource maps / Set up the EERA (European Energy Research Alliance) Ocean Energy Joint Programme together with other European research organisations.</i>
<b>Reduction of CapEx and OpEx</b> -
<b>Technology learning</b> <i>Minimising environmental impact (noise) / Reduction of amount of equipment required for monitoring / The improved understanding of environmental impacts simplifies licensing / Development of relevant design tools / Understanding of tidal resource characteristics / Understanding of sources of underwater noise for tidal energy / Resource analysis / Assisted companies in their engineering approach to offshore conditions / Scale model testing and numerical model validation / Support for supply chain / Environmental monitoring program, adaptive management team approach and philosophy / Improvement of hydraulic power-take-off system of WEC / HALT (highly accelerated lifetime testing).</i>
<b>Consenting, leasing, licensing</b> <i>Completion of Pentland Firth leasing round / Establishment of marine license / Influencing policies / Consent for Islay 10 MW tidal array / Secured long-term (20 yrs.) power purchase agreement.</i>



**Which internal targets appeared more difficult to reach than originally planned?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
10.2 %	8.2 %	5.1 %	24.5 %	24.5 %	-	18.4 %	9.2 %

Representative interview statements
<b>Marine operations experience</b> <i>Deployment (particularly wave) / Bringing some 10 MWs in the water / Navigational issues (marine traffic) / Emergency plans.</i>
<b>Device operation experience</b> <i>Put things in water that work / Minimise “lack of experience” / Getting developers wet.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Schedule / Safety.</i>
<b>Project financing</b> <i>Innovation (investment) / Marine Renewable Deployment Fund / Government budgets (keeping forecasting) / Emergence of a profitable market / Costs / Reach funding / Capital/grant funding / Raising money / The development would have been quicker if more money would have been available / Finance for environmental monitoring.</i>
<b>Business development</b> <i>2010 roadmap: 200-300 MW wave/tidal in 2020 / Development of guidance to support marine energy / Speeding up commercialisation / Biggest problem we have: struggling to engage other sectors like oil &amp; gas / To bring skills from the oil &amp; gas sector into marine energy / Access to an international (out of Europe) market / Consolidation of skills.</i>
<b>Reduction of CapEx and OpEx</b> <i>-</i>
<b>Technology learning</b> <i>Grid / Measurements of turbine wakes / Numerical model validation / Consensus over standardisation / Difficulties originated because TRLs (Technology Readiness Levels) not adequate / Reliability / Improve “materials and technology”.</i>
<b>Consenting, leasing, licensing</b> <i>Turn round times for applications / To keep consultation deadlines (time pressure) / Consenting regime.</i>

**The initiatives or activities of which stakeholders do you consider as key for the achieved progress?**

01 Government associations & trade organisations	02 Certifying authorities	03 Investors & lenders	04 Insurance companies & law firms	05 Academia & research	06 Engineering consultancies	07 Project developers	08 Owners & operators	09 Transmission system operators	10 Device manufacturers	11 Offshore contractors	12 Test site operators	13 NGOs	14 Offshore wind industry	15 Oil & gas industry
55.3 %	-	6.4 %	-	-	-	6.4 %	-	-	23.3 %	-	4.3 %	4.3 %	-	-

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
-	7.0 %	4.0 %	27.0 %	27.0 %	2.0 %	20.0 %	13.0 %

Representative interview statements
<b>Marine operations experience</b> -
<b>Device operation experience</b> <i>From tank-testing to full-scale in the water / Helping developers to get devices in the water / Getting demonstration arrays in the water.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Communication / PR (public relations).</i>
<b>Project financing</b> <i>Financial support (revenue &amp; capital) / Attract investment for the development of the sector / Provided funding for research, high-level steer / Incentive mechanisms (5 ROCs) / Making commitment and providing finances / Financial support and expertise / Provide funding / Investment / Capital grants.</i>
<b>Business development</b> <i>Continued investment in technology / Nursery sites (small scale testing) / Commitment to develop marine energy parks / Involvement of Siemens, Rolls Royce, Alstom / Supply chain support / Policy and wider support / High ambition provides signal to the world / 37m\$ awarded for technology development.</i>
<b>Reduction of CapEx and OpEx</b> <i>Value engineering / Cost reduction / Provide equipment for reasonable cost.</i>
<b>Technology learning</b> <i>Testing / Involvement in innovation projects / Develop technology / Resource modelling / Tidal array work / Collaborative research on underwater noise / Commitment to develop “reliable” technology.</i>
<b>Consenting, leasing, licensing</b> <i>Licensing sites / Supportive integration of policy, science and licensing / Planning framework / Simplify regulatory issues (consenting process) / Pragmatic approach.</i>

**Which are the main reasons why the marine energy sector has not develop more rapidly?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
8.3 %	4.2 %	-	39.6 %	14.6 %	2.1 %	29.2 %	2.1 %

Representative interview statements
<b>Marine operations experience</b> <i>Logistics: much harder to deploy in harsh environment / Underestimation of marine operations challenges / The sea is a very hard environment / No demonstration device has yet operated with a high level of availability for an extended period of time (e.g. 3 yrs.) / Complicated work / Access to appropriate testing facilities.</i>
<b>Device operation experience</b> <i>Uncertainty in device performance and reliability / Not enough focus in proving the technology.</i>
<b>Project structuring, project/risk management and EIA</b> <i>-</i>
<b>Project financing</b> <i>Difficulty in getting private investment / Willingness to fund / Policy for revenue support was not in place two years ago (now 2 ROCs in place as revenue mechanism) / More expensive than expected / More funding required / Lack of “clever” funding (focused) / Unequal injection of funds by government to support development / The necessary funding to cover project costs is far greater than was initially anticipated in the earlier formative years of the sector / With increasing costs and limited resource for acquiring the necessary investment, developers had to move at a slower pace / Squeeze on finance / Competition from offshore wind / Caution about investment / Start-up costs / Global economy / VC funding required rapid growths / Relatively low levels of support (compared to e.g. nuclear energy development in the range of 3 billion GBP) / Funding drove the engineering.</i>
<b>Business development</b> <i>Natural limitations to rate the growth / Lack of motivation (global situation, government leadership). Investment and interest from large multi-national engineering companies is only now beginning to take place at a significant scale / They needed to see proof of a concept’s merit / Previously, investment came from grant funding and angel investment - now that investment is being made from large engineering companies, quicker progress is being made / The industry presents itself as being at a more advanced state of development than it really is which is leading external stakeholders (e.g. policy makers and funding bodies) to direct their resources towards tackling barriers other than the ones the industry immediately faces / Trying to sell projects for which the technology is not ready / Little involvement of large OEMs (original equipment manufacturers) / Lack of understanding (expectation of sector to deliver very quickly).</i>
<b>Reduction of CapEx and OpEx</b> <i>Commercial pressures leading to no cooperation / Cost to fabricate and deploy devices / High cost of electricity.</i>
<b>Technology learning</b> <i>Technically challenging / Technology not there or not properly developed / Materials / Too much focus on incremental technology changes / Diversity of technology / Technology not proven / Initial naivety / No short-cuts, staged development / Over-optimistic developers / Too many different concepts under development / Technology barriers not addressed adequately (e.g. subsea infrastructure) / Lack of collaboration in the industry.</i>
<b>Consenting, leasing, licensing</b> <i>Cost and uncertainty in permitting / Lack of firm decisions from government / Uncertainty about the economic payback of projects and limited knowledge about life expectancy of devices without intensive sea trials held back rapid development / Early life faults need to be engineered out of commercial products prior to deployment.</i>

**In which areas is research most required to accelerate the development of marine energy?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
16.0 %	11.0 %	1.0 %	8.0 %	7.0 %	4.0 %	44.0 %	9.0 %

Representative interview statements
<b>Marine operations experience</b> <i>Deployment and installation / Resource interaction / Subsea reliability / Careful planning of cable routing / Technologies which enable impact monitoring (effects on wildlife) / Demonstrations (array and single device) / Marine mammals / Installation methodology / Underwater noise / At sea deployment and retrieval operations.</i>
<b>Device operation experience</b> <i>Field of testing of demonstration devices / O&amp;M methodologies / Array-scale maintenance / Design tools to help optimise and facilitate cost effective array scale development, consideration of multiple aspects of an array scale project are required, from installation, moorings, to O&amp;M / Routing and interconnection of power cables in large arrays / Research on multiple aspects for arrays / Reliability and maintainability / Deployment of arrays.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Risk management / Environmental impact / Hydraulic impact studies.</i>
<b>Project financing</b> <i>Economic feasibility of marine energy / Financial and cost modelling / Development of technology is presently too expensive / Identify where the funding should best go to / Improve the cost reduction by using new materials / Getting cost down (maintenance cost very high at present).</i>
<b>Business development</b> <i>Array-scale design / Short term energy storage / Cross-interaction between renewable energies / Strategic planification / Roadmaps / Industry programmes have shorter timeframes (1 year) than academia.</i>
<b>Reduction of CapEx and OpEx</b> <i>Cost reduction / Energy yield certainty.</i>
<b>Technology learning</b> <i>Offshore transmission / Moorings, fixings / A lot will be needed on optimising electrical systems / Power export cables (very expensive, very important) / Seabed mounted cable connections / System-level optimisation and engineering / Turbulence / Sensors and controls / Structural support, extreme loadings / Power take-off / Whole system evaluation / Installation methods – increase the understanding of methods for cost-effective installation and retrieval to minimise operational and O&amp;M costs / Reliability and integrity of devices / Larger-scale model testing / Electrical cabling and infrastructure – technical challenges with the location of infrastructure in turbulent and challenging locations / Grid integration / Reliability of components and systems / Hydrodynamics (modelling of arrays with multiple devices) / Cheap ways to harvest marine energy / Reliability optimisation / Focus on common components and not specific technology / Clear recognition that system engineering is crucial / Offshore electrical infrastructure / Improvement of the power take off, improve the efficiency of the energy transformation / Fisheries and marine life interaction studies / Generator design, performance, efficiency / Balance of plant.</i>
<b>Consenting, leasing, licensing</b> <i>Interactions with SPAs (Special Protection Area) and SACs (Special Area of Conservation) / EIA need to cover marine wildlife / Consenting evidence / Environmental interaction / Environmental impacts / Mammals, fishery.</i>

## 4 COST ASPECTS

### Where do you see the greatest concerns for delays and cost-overruns in marine energy projects?

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
37 %	9 %	4 %	10 %	9 %	1 %	17 %	13 %

Representative interview statements
<b>Marine operations experience</b> <i>Availability of heavy marine services / Under-estimation of marine operations challenges / Weather windows (adequate use of forecast) / Weather risk and logistics / Work windows / Installation, operation and maintenance / Vessel availability / Offshore operations / Underestimating marine conditions (turbulence, waves) / Difficult installation in offshore locations / Working offshore is generally difficult and expensive / Direct experience of cost overruns due to weather-induced delays / Availability of installation vessels / Device deployment, weather impacts, etc. / Harsh marine environment / Installation and deployment techniques / Competition with oil &amp; gas industry supply chain (DP vessels).</i>
<b>Device operation experience</b> <i>Failure of devices / Construction / O&amp;M / Reliability and performance / Installation and operations.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Project management and interface controls / Underestimation of risks and uncertainties / Planning for vessel use months in advance is difficult for early stage projects / Environmental issues.</i>
<b>Project financing</b> <i>Lower than expected performance could increase levelised cost / Installation costs and delays due to weather windows (with most current marine energy installations requiring vessels from the oil &amp; gas industries, the spot market prices can fluctuate significantly and result in significant cost overruns if vessels are required for longer than initially thought) / Securing investment / Manufacturing cost, transport and installation cost / First time, unknown costs / Cost were generally underestimated.</i>
<b>Business development</b> <i>Supply chain / Building up experience for the sector / Monopoly suppliers for key components / The ability of device developers to supply multiple devices on time and budget / Contractor-subcontractor management.</i>
<b>Reduction of CapEx and OpEx</b> <i>Marine infrastructure is expensive / High cost of deployment vessels / To achieve market success in Nova Scotia, tidal generators must not cost more than say \$5 million CAD/MW (~3.2 mEUR/MW) with a resulting energy costs of &lt;\$140/MWh (~9c€/kWh).</i>
<b>Technology learning</b> <i>Lack of experience of developers in many aspects / Complexities of grid interconnection / Siting of arrays (sand-banks) / Reliability &amp; durability / Grid connection delays (unfair on renewable energy located far away from population centres, but at area of greatest resource) / Without assured grid connection, no project will go ahead (delays to vital electrical infrastructure upgrades cause costs to rise and delay project construction schedules) / Uncertainty around technology performance and technology readiness / Technology progress / Poor manufacturing / Test failures / Developers should invest more time and money in wave-tanks and part-scale testing.</i>
<b>Consenting, leasing, licensing</b> <i>Certification (technical and environmental) / Licensing and foreshore planning / Stringent requirements for environmental impact and proving that device will not produce negative environmental effects / Consenting and development process / Legal permit process / Regulation.</i>

**Where do you see potential to get the cost for utility-scale project implementations down?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
25 %	5 %	10 %	5 %	10 %	7 %	38 %	-
Representative interview statements							
<b>Marine operations experience</b> <i>Improved deployment technology and retrieval methods / Use of lower cost installation vessels / Using experience already gained in oil &amp; gas and defence industries so that common mistakes are not repeated / Development of optimum installation and O&amp;M strategies through modelling / Floating support structures / Optimised installation boats / Sea testing of equipment (life cycle testing) / Develop pilot zone (developers pay fee) / Availability of shipyards and manufacturing sites / Catamaran-type vessel capable of deploying in tidal race.</i>							
<b>Device operation experience</b> <i>Array-level design and system integration / Pilot projects / Development of next generation(s) devices / Prove that systems work reliably / Availability record / Better performance.</i>							
<b>Project structuring, project/risk management and EIA</b> <i>Production capability / Collaborative contracts / Contract structuring / Contract standardisation (as in onshore wind) / Structured engineering process (doing a lot of work upstream, select the right solutions).</i>							
<b>Project financing</b> <i>Concur with the Carbon Trust Marine Energy Accelerator (MEA) analysis / Long-term revenue streams / Shared funding.</i>							
<b>Business development</b> <i>Scale of the industry / Volume production and improvements in engineering (confidence in design margins through experience, new materials etc.) / Supply chain development / Serial production / Streamline production / Large-scale manufacturing / Supplier competition / Closer collaboration between OEMs and project developers.</i>							
<b>Reduction of CapEx and OpEx</b> <i>DECC study on cost reduction in wind power / Low-cost strategies for interconnections of devices in arrays / It is important to focus on cost of electricity and not CapEx (optimum cost of electricity may involve higher CapEx through the use of higher quality components and a certain degree of “over-engineering” - Pushing down on CapEx in isolation could be counterproductive / Economies of scale.</i>							
<b>Technology learning</b> <i>Bringing in offshore oil &amp; gas marine operations expertise / Structural design and materials costs / Shared learning by developers - this will prevent the same mistakes being made time and again / Reduce likelihood of early stage failures / Streamline manufacturing / Improve productivity / Increased device scale / Optimised foundations and moorings / Grid connection sharing between multiple projects / Structural design and materials costs / Sub-sea electrical connectors / Technology convergence / Bring in major industrial expertise / Upscaling of devices (kW to MW) / Learning by doing (from prototype deployment and testing in real offshore environment / Standardisation (look at volume manufacturing) / Material improvement / Increase component output and efficiency / Improve energy production capacity / Replication &amp; duplication in manufacturing process / Availability of TECs and WECs as reliable end-products / Manufacturing and industrialisation / Much more cooperation from project &amp; technology developers / Over-engineering in oil &amp; gas standards - elaborate own standards.</i>							
<b>Consenting, leasing, licensing</b> -							

**What are the main factors driving up the insurance cost?**

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
10.8 %	8.6 %	8.6 %	6.5 %	24.7 %	2.2 %	38.7 %	-

Representative interview statements
<b>Marine operations experience</b> <i>Weather risk and logistics / Extreme weather conditions / Physical environment / Challenging environment.</i>
<b>Device operation experience</b> <i>Lack of experience / Device failures / Incompletely documented device / Lack of proven long term operation.</i>
<b>Project structuring, project/risk management and EIA</b> <i>Lack of risk controls / Inadequate demonstration of risk management / “No standards - no results” / Demonstrate lower level of risks than thought.</i>
<b>Project financing</b> <i>Current financial environment / Claims by past projects / Price of high risks.</i>
<b>Business development</b> <i>Small companies / Lack of major industry success stories / Lack of experience from insurance / No reference projects, so insurance companies estimate “safe” margins / Level of risk / Unfortunate experience by others / Risk assessment analyse / Very limited insurance market at present (even for offshore wind) / Derivative market (will follow marine energy development).</i>
<b>Reduction of CapEx and OpEx</b> <i>History (high level of claims) / Cost of offshore failures / Unproven contractors to reduce costs.</i>
<b>Technology learning</b> <i>Lack in understanding the sector / Technology risk / Challenging technology / Realise likelihood of early stage failure / Experienced difficulties / Experimental nature / Reliability &amp; durability / Uncertainty of reliability, safety, commercial return = very high risk / Many unknowns at this stage in the development of ocean energy projects / Unproven technology and methods / Uncertainties (proven technology is required) / Too many unknowns / Lack of knowledge / Unfavourable experience in offshore wind.</i>
<b>Consenting, leasing, licensing</b> -



**What measures can be taken to avoid experienced cost increase in offshore wind?**

	Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
Measures to reduce “complexity of planning process”	3 %	6 %	9 %	-	21 %	3 %	12 %	45 %
Measures to reduce “supply chain bottlenecks”	9 %	-	13 %	-	61 %	4 %	13 %	-
Measures to increase the “equipment reliability”	14 %	17 %	9 %	-	6 %	3 %	49 %	3 %

<b>Representative interview statements</b>		
<b>Complexity planning process</b>	<b>Supply chain bottlenecks</b>	<b>Equipment reliability</b>
<b>Marine operations experience</b>		
<i>Better knowledge of projects.</i>	<i>Ensure port infrastructure is established / Aim on smaller and simpler vessels.</i>	<i>Better marine operations for recovery / Test in open sea conditions / Importance to design for installation and maintenance / Modularity / Redundancy.</i>
<b>Device operation experience</b>		
<i>Adherence to best practice by developers / Experience.</i>	-	<i>Improved performance monitoring / More testing / Monitoring of equipment / More tests (test sites are essential).</i>
<b>Project structuring, project/risk management and EIA</b>		
<i>Planning process is not complex / Develop industry-wide planning protocols / Wait until complexities have sorted out in offshore wind.</i>	<i>Existence of potential market for supply chain / Cooperation supply chain &amp; developer / A bottleneck in the supply chain is expected (investments have 2 yrs. of delay) / Accurate roll-out forecasting.</i>	<i>Coordinated approach to collect data on failures / Understanding environment.</i>
<b>Project financing</b>		
-	-	-
<b>Business development</b>		
<i>Proportionality / Clear objectives / Complexity of the planning process was identified as causing slower than expected progress, but is not as a significant contributor to cost escalation / Clarity of objections / Early engagement on the environmental assessment / Early stakeholder engagement and consultation.</i>	<i>Not relevant at present / Not clear if this is a problem / Not at present / Develop UK supply chain capabilities / Get the supply chain existing / Market signals for demand forecasting / Early notification to suppliers / Creation of "cluster" of suppliers / Vessels and ports / Lockdown of project design / Realism in schedules / Establish early stage supply / There is none at present / Identification of bottlenecks early on / Not big enough yet.</i>	<i>FMEA (Failure Mode and Effects Analysis) / Supplier competition.</i>
<b>Reduction of CapEx and OpEx</b>		
<i>In the statistics this is all related to water depths and distance to shore.</i>	<i>Become an attractive investment proposition.</i>	<i>Compromise reliability and cost.</i>



Complexity planning process	Supply chain bottlenecks	Equipment reliability
<b>Technology learning</b>		
<i>Evidence base / Standardized design approaches / Better sharing of engineering and environmental data / In France: lack of dialog.</i>	<i>Transfer of technologies from offshore wind and other sectors / Cooperation between developers for similar equipment / There are none at present for MCT.</i>	<i>Innovation and testing / Materials / Apply concepts from offshore wind / More focus on reliability in system design / Device design / Stop dreaming - start engineering with the harshest operating environment in mind / Sharing of lessons learned between projects / Component redundancy / Design for maintainability / Design out complexity and failure points / Reliability modelling / Techno-economic optimisation / Better performance / “Learning by doing” / Major industrial expertise / Development toward "standard design solutions (e.g. number of rotor blades)" / Being focussed and capture the knowledge.</i>
<b>Consenting, leasing, licensing</b>		
<i>Improved environmental monitoring to facilitate consenting / Having a single regulatory body / Consistency between England (Marine Management Organisation) and Scotland (Marine Scotland) / Provision of guidance on how to get consent / Licensing has been greatly simplified in the last few years / Provide clarity on environmental certification requirements / Provision on wildlife by collaboration of industry, The Crown Estate, The Scottish Government / Single point of handling of process / Appeals process / Difficult maybe the involvement of public authorities since the beginning of the projects / Clear regulatory process / Local communication / Single license application / Getting consent (more difficult abroad, Marine Scotland doing well) / Pragmatic regulatory stance.</i>	-	<i>Certification.</i>

## 5 MAIN IMPACT FACTORS ON “FULL-COMMERCIAL POWER GENERATION”

### Positive (supporting/accelerating) / Negative (hindering/delaying)

Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
3 / 8 %	7 / 3 %	- / -	19 / 21 %	35 / 22 %	4 / 6 %	8 / 14 %	24 / 26 %

Representative interview statements	
Positive	Negative
Marine operations experience	
<i>Resource availability / EMEC / Showcase commercial scale project(s) / Support of administration of test sites.</i>	<i>Grid constraints / No port infrastructure / Test failures / Critical events regarding H&amp;S (negative press) / Environmental impact (in case of disastrous event).</i>
Device operation experience	
<i>Providing confidence in the performance of core technologies / Successful demonstrations / Proven O&amp;M models / Technology reliability / Prototype experience.</i>	<i>Uncertainty about the technologies (very experimental) / Technology performance / Technology failures / Unrealistic timelines (devices, developers).</i>
Project structuring, project/risk management and EIA	
-	-
Project financing	
<i>Funding support / Financial incentives to generate marine energy (tariff) / Fiscal measures to drive early stage deployments / ROCs prices increasing / Increased innovation funding mechanisms / Long-term commitment from government - FIT (feed-in tariff) schemes / Increasing oil &amp; gas prices / Utility and OEM buy-in / ROC (renewable obligation certificate) mechanism and capital grant funding / National, state research and development funding programs / Investment from industry (plausibility) / Predictable return stream (long-term stable investment).</i>	<i>Global economic situation / Continued financial instability / Investment climate / High cost of wave and tidal / Fragmented funding / Overall financial environment / Investor confidence / Grid: both underwriting grid development costs and excessively high use of system charges at extremities (e.g. Scottish islands, where most of marine resource resides) of UK transmission network / Access to capital / Distrust in investment environment / The investment community is nowhere to be seen - too risky.</i>
Business development	
<i>Decarbonisation of power industry / Strong, consistent and stable political support (absolute key for the industry) / Clustering (device developers / test sites) / Demand for new (additional) generation capacity / Evidence base / Climate change targets / Knowledge transfer from relevant industries (oil &amp; gas skills, bring down cost) / Encouraging research, technology development in coordination with testing facilities / “Green” technology / Resource availability and reusability / Geographic location (available resource in UK and Ireland) / Free energy source / Industry (job opportunities) / Low carbon / Overall energy</i>	<i>Suspect political support / Lack of industry success stories / Associated risk of carbon reduction (global, European, national) / Low ability of developers to work together / Too many utility options (“they can invest in gas, solar, wind, ...”) / Too many developers / Environmental pressures / Fragmented initiatives by unexperienced parties / Subsidy-driven instead of market-driven developments / Failed demonstrations / Weakening political support / Technology Readiness Level (TRL) oversold / EU environmental legislation / Lack of credibility / Lack of a coherent strategy in the UK (DECC, Crown Estate, Government, industry,</i>

Positive	Negative
<p><i>environment (marine energy seen as a solution) / Engagement industry &amp; academia / After 2020 renewable targets / Market-internal competitively / Commitment of Original Equipment Manufacturers (OEM's) to sector / Collaboration and consolidation between companies / Development of offshore wind / Government support and rules to be in place &gt; 20 yrs. / Energy need / Critical mass of engaged engineers and scientist (EMEC very useful, learning from each other).</i></p>	<p><i>universities) / Competition between the renewable energies / Competition with on-/offshore wind / Grey zone (next 5 yrs. are decisive) / More collaboration (too many people doing the same things) / Start-stop incentives by the government / Need for large-scale investments (ABB, Siemens, Alstom) / Long times required for large companies to commit to marine energy / Fluctuating or unclear political support (feeling of developing for only a governmental period).</i></p>
Reduction of CapEx and OpEx	
<p><i>Cost improvement (realistic) / Cost-effective way to harvest marine energy (techno-economic optimum) / Minimising levelised cost of electricity / Ability to bring cost of power generation down.</i></p>	<p><i>Cost of devices / Early commercial pressure / Long delays in projects coming on line / High cost compared to existing generation with hidden subsidies / Outrageously expensive deployment costs / Overall financial arrangement (CapEx, electricity price, feed-in tariff or equivalent system, public funding availability etc.).</i></p>
Technology learning	
<p><i>Predictability (mainly tidal) / Standards / Focus on reliability / Focussed support of technology development &amp; pilot deployment / Sea test facility / Academic research / Step-by-step approach (complete one by one) / Testing of full-scale prototypes (at EMEC etc.) / Market maturity / Top OEM's have to accelerate technology development.</i></p>	<p><i>Engineering challenge / Perception of high cost and unproven reliability / Limited knowledge sharing in industry / Uncertainty about reliability / Required technology maturity / Grid infrastructure / Technology readiness / Fragility in technology / Very, very difficult engineering challenge for marine energy / Lack of sharing (bad) experiences (explaining why things went wrong) / Worst scenarios are imagined (if no communication of failures) / Proving technologies (convergence of designs) / Technological barriers / Unclear transition from pilot to commercial scale.</i></p>
Consenting, leasing, licensing	
<p><i>Government support mechanisms / Maintaining political commitment / Efficient management of the consenting process / Climate change (strict political sentiment) / Fear of obvious alternatives / Public support, local government support / Clean energy / Public support, economic benefits and job creation / Climate change, carbon reduction / Clear governmental procedures / Political leadership and (consistent) policy support / Subsidiary mechanism / Supporting program (FP7, country program, local program) / Ability to secure a seabed from The Crown Estate (which doesn't exist in that form in many other countries) / Regulatory framework (e.g. grid connection) / Public awareness and support of renewable energy / Regulator support / Tidal energy must be part of the Canadian Government's priority list / Overall EU commitment 2020-20 / Stable and predictable policy and subsidies / Energy independence / The public is on side with tidal energy.</i></p>	<p><i>Consenting delays / Conflicts of interest (fishermen, shipping routes) / Lack of public support / Uncertainty of getting grid connection in time / Lack of political support / Policy decision delays / Too many environmental groups involved / Grid updating strategy / Lack of consensus from different countries on support mechanisms / Local fishermen disagreement / Political patience / Environmental lobby groups creating increasing number of new restrictions on development / Missing recognition of renewable energy in public / Confused regulatory process and policy / Moving political positions / Lack of support of administration (legal framework) / Consents for early projects (dependent on regulators getting sufficient "comfort" from prototype deployments) / Unclear regulatory framework / Delay and lack of policies / Complex stakeholder coordination (e.g. international waters) / Lack of appropriate marine spatial planning.</i></p>

## 6 RISKS

### Which are the key risks in commercial-scale marine energy per project phase?

	Marine operations experience	Device operation experience	Project structuring, project/risk management and EIA	Project financing	Business development	Reduction of CapEx and OpEx	Technology learning	Consenting, leasing, licensing
Project initiation and concept	6 %	-	12 %	18 %	24 %	-	29 %	11 %
Planning and design	6 %	-	19 %	-	6 %	-	31 %	38 %
Manufacturing and testing	-	14 %	21 %	-	36 %	-	22 %	7 %
Erection and commissioning	60 %	-	13 %	-	-	13 %	14 %	-
Commercial operation	20 %	40 %	13 %	7 %	-	-	20 %	-
Decommissioning	22 %	-	11 %	-	11 %	22 %	11 %	23 %

#### Representative interview statements

##### Project initiation and concept

*Planning, technology prove / Resource and site conditions / Securing lease from The Crown Estate to get a piece of seabed / Over-optimism - especially cost of electricity / Selecting the most appropriate site / Identifying suitable site locations, lack of proven technologies / Lack of resources / Limited data / Lack of understanding of energy resource / No “excellent” examples / proven technology / Impractical projects / Raising of capital without over promising / Decisions made at the conceptual stage can have a larger impact on project outcomes than ones made later in the development process, so although this might not normally be viewed as a high risk phase, in fact it is / Project scope undefined, lack of financing, partnerships not established / In France: dialog with local stakeholders / Energy resource / Access to the grid / Site selection / Device performance at partial load.*

##### Planning and design

*Planning, technology prove / Resource and site conditions & stakeholder interests / Securing consent from Marine Scotland, EIA, cost of surveys on wildlife / Consenting / Failing to engage regulator early and continuously / Lack of clarify of planning requirements, limited system-level understanding / Lack of resources, time pressure, limited data, lack of systematic approach to risk / Late design information / Lack of project structuring knowledge to arrive at a bankable proposition / Lack of comprehensive design tools / Appeals process at planning; reluctance to spend finance / Consenting risk also falls in this phase and could be significant / Safety factors no considered, data inaccuracies or lack of, lack of resources / Timescales / Change of design after submitting the plan / Delay due to environmental issues.*

##### Manufacturing and testing

*Cost overrun, time / Limiting resources of time / Attract funding to move from demonstrators to full-scale / Survivability / Supply chain focussed on other sectors, testing costs prohibitive / Lack of production capabilities, no supply chain / Late manufacturing / High cost to test, customized components and systems / Gaps in the supply chain and quality of outsourced components / This, together with installation, is where serious cost starts to be incurred and so if anything goes wrong the financial implications can be big / Quality control, 3rd party certification / Should be able to test onshore (too expensive in water) / Supply chain immaturity / Standards aren't applied and quality.*

##### Erection and commissioning

*Cost overrun, weather / Cost of installation, H&S / Working conditions in hostile environment / Increasing cost (lack of planning or experience) / Ensuring marine operations challenges are understood and addressed / No specialised vessels and personnel / Weather risk / Availability of deployment infrastructure / Insurability of the project phases, costs over 3rd party cables, etc. / Same as for manufacturing and testing / Improper planning, equipment not suitable, weather challenges, cost overruns / Marine conditions (accessibility, weather window) / Weather / Marine operation / Delay by inefficient commissioning and downtimes.*

**Commercial operation**

*Lack of reliability and maintenance, resource not fully understood / Weather / Maintenance costs, having a guaranteed market to buy electricity / Survivability / Poor reliability, reduction in fiscal incentives / No experience / Weather risk and durability / Unplanned maintenance / Speed of marine operations for O&M activities / The technology is unproven and so likely to have high failure rates leading to high O&M costs and low energy output (a double whammy, raising costs and lowering revenue simultaneously). An unexpectedly high failure rate could therefore have a big impact on project economics (less kWhs produced, maintenance issues, costs) / Accidents / Reliability / Support mechanism by government / Availability.*

**Decommissioning**

*“Too early to say” / Lack of consideration of decommissioning process / Under-estimation of effort needed and consequent cost increases / No experience / Look for renew rather than decommissioning / Inability to decommission due to bio fouling/corrosion / Consent clauses regarding what can and cannot be left in-situ / This only a low risk because it involves well established techniques, is not dependent on device performance and is (hopefully) many years in the future, giving it a small NPV (net present value) / Environmental impacts, costs / Environmental legislation / Availability / Weather window / Vessels.*

**Risk transfer or risk propagation**

Reference is made to the main thesis text:

Chapter	5	Primary interview results & statistical findings
Section	5.5	Risks
Paragraph	5.5.2	Risk transfer and risk propagation processes

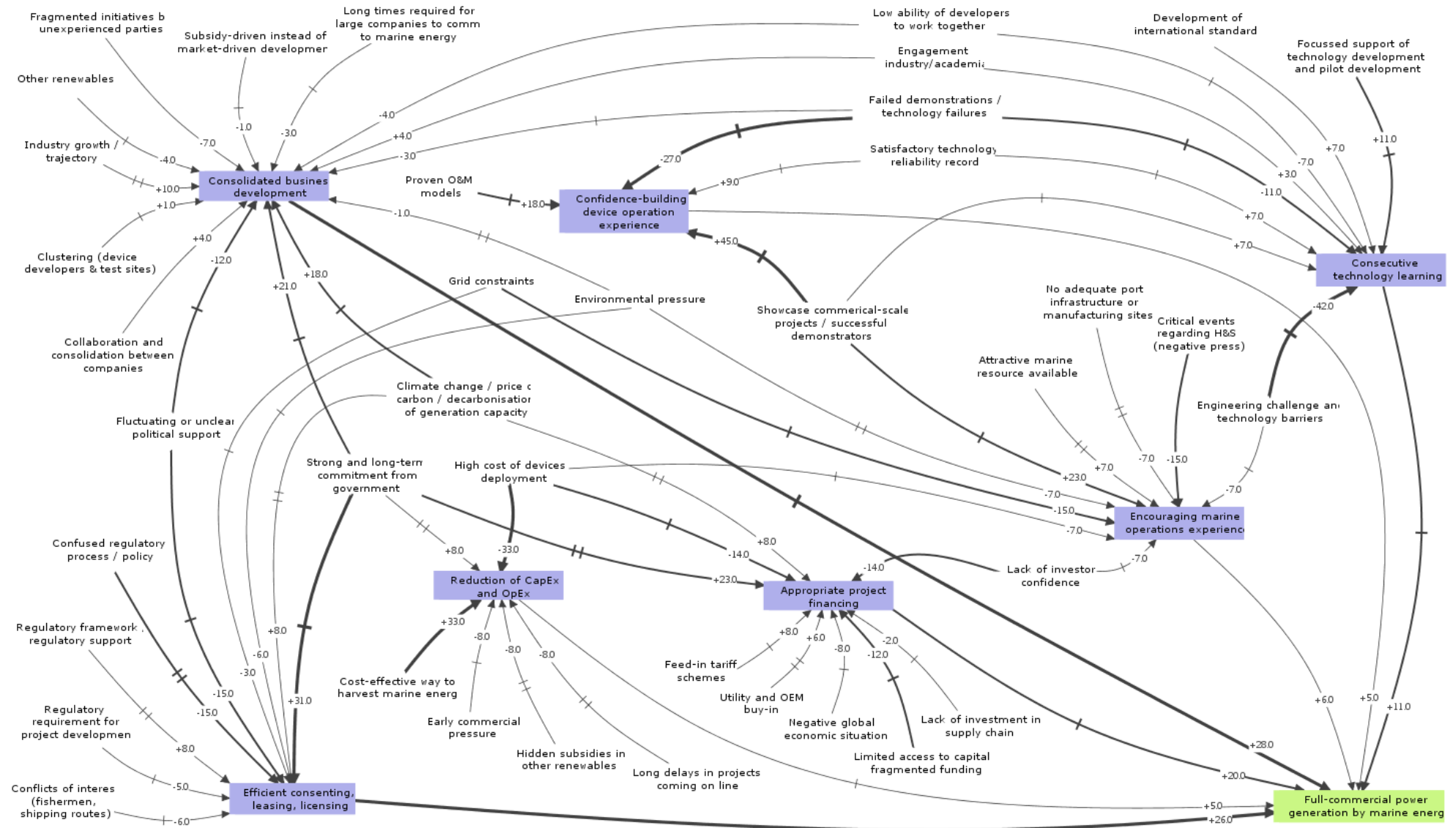
**Correlation of each risk type to an estimated risk level**

Reference is made to the main thesis text:

Chapter	5	Primary interview results & statistical findings
Section	5.5	Risks
Paragraph	5.5.3	Correlation of risk types to estimated risk levels

- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.1      Causal diagram**

## Model 1 (basic): Full-commercial power generation by marine energy



- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.2      Distribution of interview replies**
- E.1.2.1    Replies per stakeholder**



[illegible]

- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.2      Distribution of interview replies**
- E.1.2.2   Configuration table**

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW\_Q5\_EVALUATION\_replies\_234 / 5C - 12.08.2017 - 19:25 Page 1 of 7

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW Q5 EVALUATION replies 234 / 5C - 12.08.2017 - 19:25 Page 2 of 7

5		Project financing			
<b>25 Positive (supporting/accelerating)</b>		<b>22</b>	<b>INT</b>	<b>DEL</b>	<b>4</b>
118		11	0,23	I	Strong and long-term commitment from government
		4	0,08	m	Feed-in tariff schemes
		4	0,08	I	Climate change / price of carbon / decarbonisation of generation capacity
		3	0,06	I	Utility and OEM buy-in
<b>34 Negative (hindering/delaying)</b>		<b>25</b>	<b>INT</b>	<b>5</b>	<b>0,50</b>
116		6	0,12	m	Limited access to capital / fragmented funding
		7	0,14	m	High cost of devices / deployment
		4	0,08	m	Negative global economic situation
		7	0,14	m	Lack of investor confidence
		1	0,02	m	Lack of investment in supply chain
Total					
59					
234					
Impact strength on final target					0,95
Absolute number of replies [abs.]:		47			
Percentage-wise distribution of replies [%]		20			

5		Business development			
<b>25 Positive (supporting/accelerating)</b>		<b>40</b>	<b>INT</b>	<b>DEL</b>	<b>6</b>
118		14	0,21	m	Strong and long-term commitment from government
		7	0,10	I	Industry growth / trajectory
		12	0,18	m	Climate change / price of carbon / decarbonisation of generation capacity
		1	0,01	m	Clustering (device developers & test sites)
		3	0,04	s	Engagement industry/academia
		3	0,04	s	Collaboration and consolidation between companies
<b>34 Negative (hindering/delaying)</b>		<b>25</b>	<b>INT</b>	<b>8</b>	<b>0,35</b>
116		3	0,04	m	Other renewables
		8	0,12	m	Fluctuating or unclear political support
		1	0,01	I	Environmental pressure
		3	0,04	s	Low ability of developers to work together
		5	0,07	s	Fragmented initiatives by unexperienced parties
		1	0,01	m	Subsidy-driven instead of market-driven developments
Total		2	0,03	m	Failed demonstrations / technology failures
59		2	0,03	m	Long times required for large companies to commit to marine energy
234					
Impact strength on final target					0,93
Absolute number of replies [abs.]:		65			
Percentage-wise distribution of replies [%]		28			

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW\_Q5\_EVALUATION\_replies\_234 / 5C - 12.08.2017 - 19:25 Page 5 of 7

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW Q5 EVALUATION replies 234 / 5C - 12.08.2017 - 19:25 Page 6 of 7

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW\_Q5\_EVALUATION\_replies\_234 / 5C - 12.08.2017 - 19:25 Page 7 of 7

**E            System dynamics computer models**

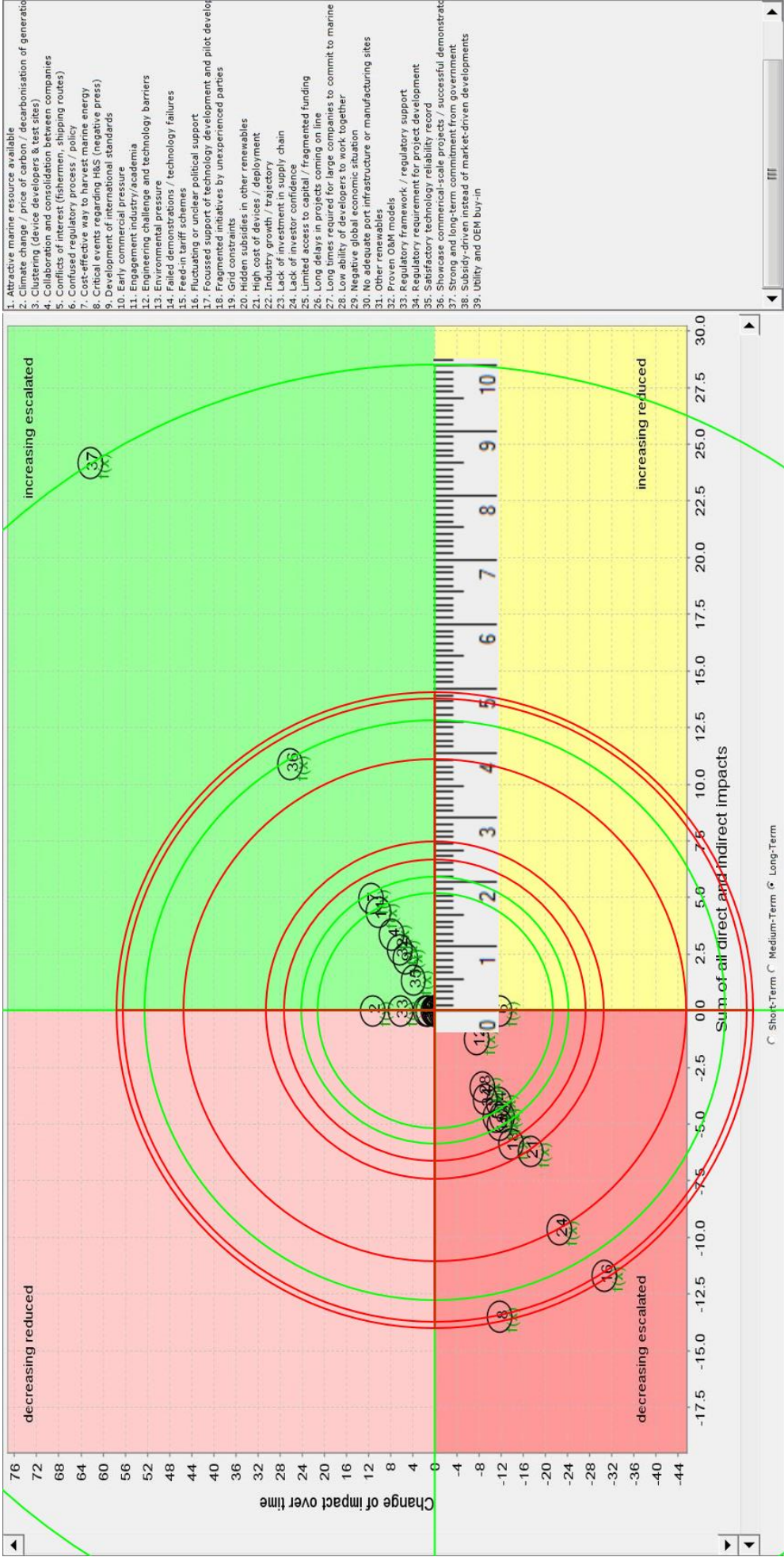
**E.1         Model 1: Full-commercial power generation by marine energy**

**E.1.3      Insight matrix**



Model 1 (basic): Full-commercial power generation by marine energy

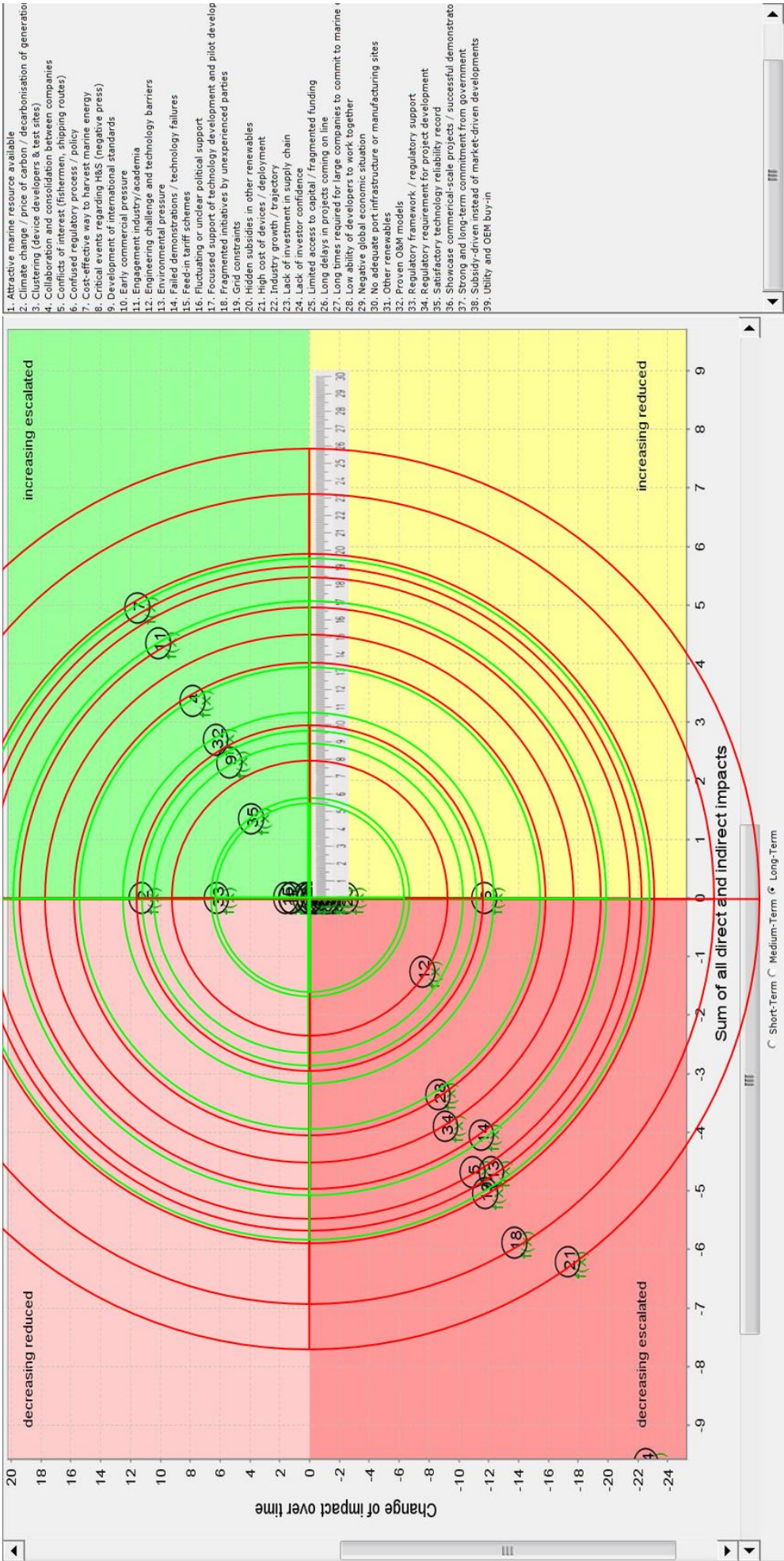
Overall / for calibration.





Model 1 (basic): Full-commercial power generation by marine energy

Detail.



- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.4      Sensitivity and robustness**
- E.1.4.1    Plausibility check**

**Comparison table: Interview data and results by SD-model**

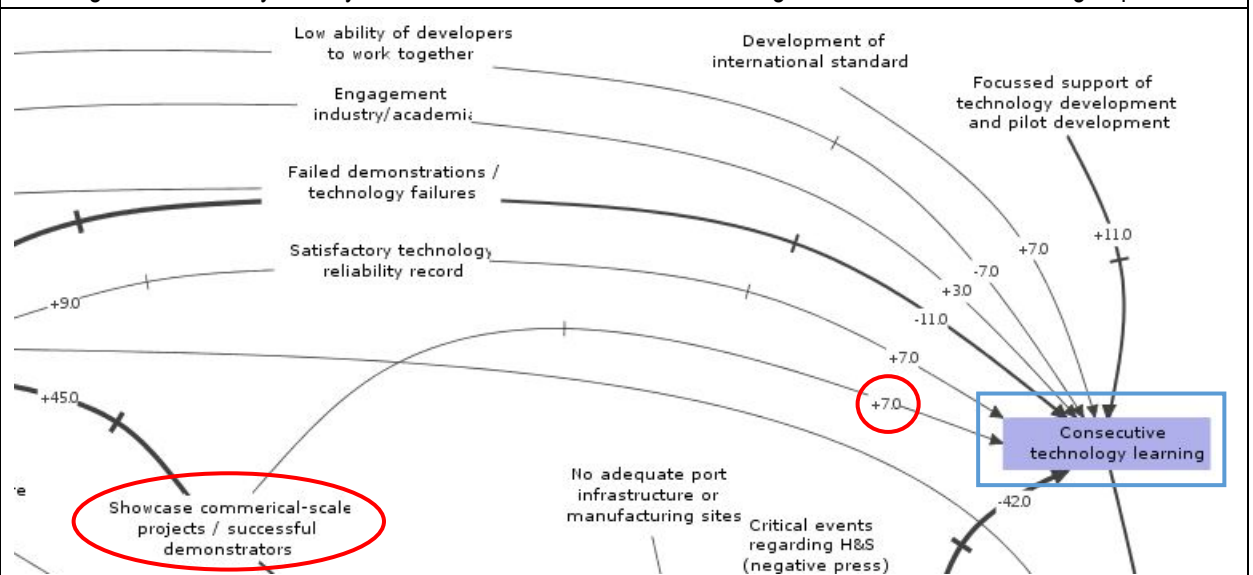
Generic Term	Interview data [abs.]	Interview data [norm.]	SD-model 1
Strong and long-term commitment from government	45	100	100
Climate change / price of carbon / decarbonisation of generation capacity	21	47	10
Fluctuating or unclear political support	17	38	49
Engineering challenge and technology barriers	12	27	8
High cost of devices / deployment	12	27	26
Showcase commercial-scale projects / successful demonstrators	10	22	45
Confused regulatory process / policy	9	20	10
Failed demonstrations / technology failures	8	18	17
Lack of investor confidence	8	18	39
Industry growth / trajectory	7	16	<2
Environmental pressure	6	13	19
Limited access to capital / fragmented funding	6	13	<2
Fragmented initiatives by unexperienced parties	5	11	23
Low ability of developers to work together	5	11	14
Regulatory framework / regulatory support	5	11	5
Conflicts of interest (fishermen, shipping routes)	4	9	18
Cost-effective way to harvest marine energy	4	9	20
Engagement industry/academia	4	9	17
Feed-in tariff schemes	4	9	<2
Grid constraints	4	9	20
Negative global economic situation	4	9	<2
Collaboration and consolidation between companies	3	7	13
Focussed support of technology development and pilot development	3	7	<2
Other renewables	3	7	<2
Regulatory requirement for project development	3	7	15
Satisfactory technology reliability record	3	7	6
Utility and OEM buy-in	3	7	<2
Critical events regarding H&S (negative press)	2	4	48
Development of international standards	2	4	9
Long times required for large companies to commit to marine energy	2	4	<2
Proven O&M models	2	4	11
Attractive marine resource available	1	2	<2
Clustering (device developers & test sites)	1	2	<2
Early commercial pressure	1	2	<2
Hidden subsidies in other renewables	1	2	<2
Lack of investment in supply chain	1	2	<2
Long delays of projects coming on line	1	2	<2
No adequate port infrastructure or manufacturing sites	1	2	<2
Subsidy-driven instead of market-driven developments	1	2	<2
total	234		

- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.4      Sensitivity and robustness**
- E.1.4.2    Removal of subsets of sample population**
- E.1.4.2.1 Showcase commercial-scale projects / (...) demonstrators**

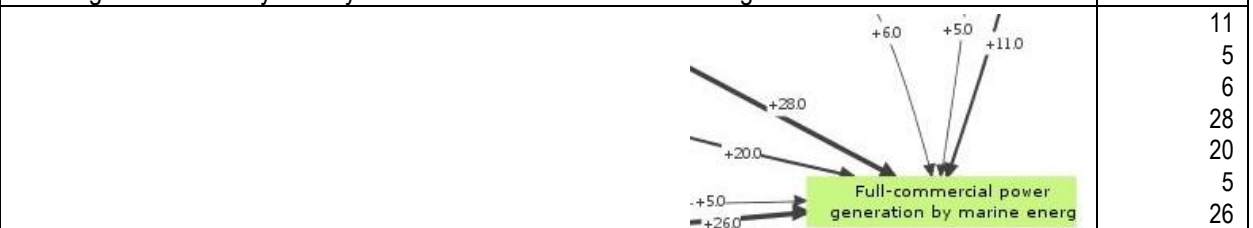
**1 Generic term: Showcase commercial-scale projects / successful demonstrators (#36)****1.1 Group term: Consecutive technology learning****1.1.1 Original SD-model**

	No. of replies	%-value
Focussed support of technology and pilot development	3	11
Development of international standards	2	7
Low ability of developers to work together	2	7
Engagement industry / academia	1	3
Failed demonstrations / technology failures	3	11
Satisfactory technology reliability record	2	7
<b>Showcase commercial-scale projects / successful demonstrators</b>	<b>2</b>	<b>7</b>
Engineering challenge and technology barriers	11	42
Total:	26	

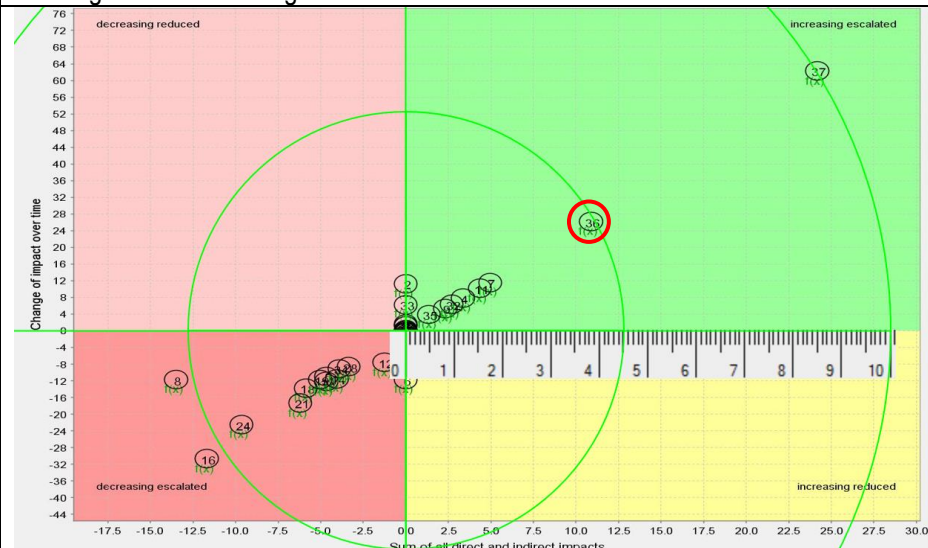
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:

Impact strength by original model as in Table 12 (#36):  
**45**

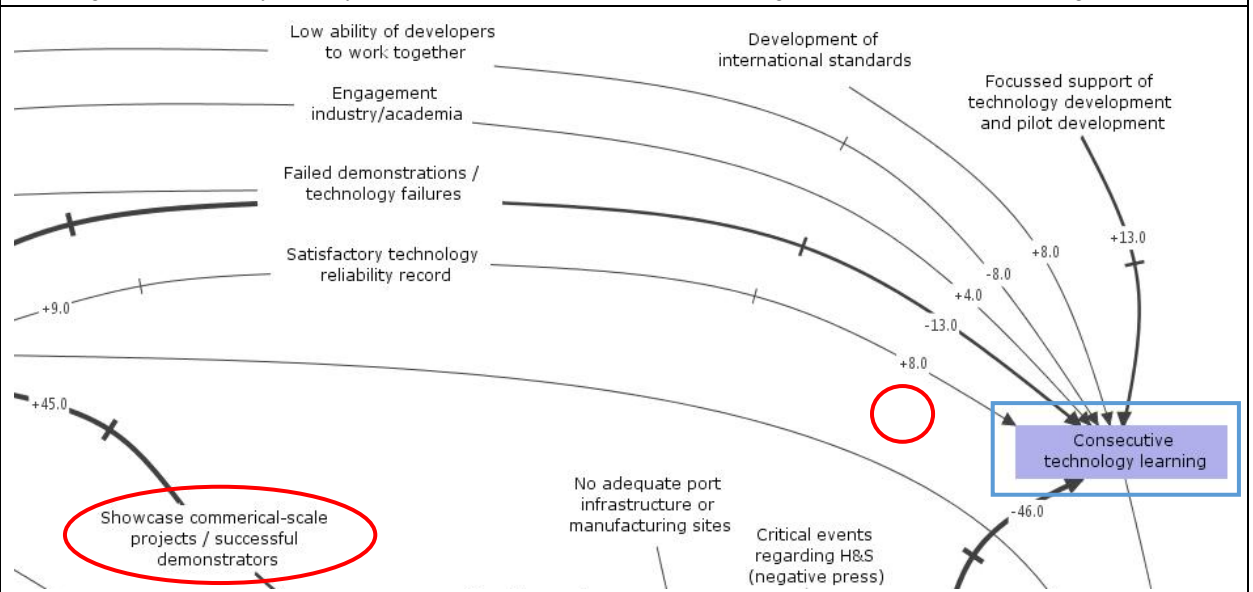


### 1.1.2 Sensitivity analysis “-10% respondents”

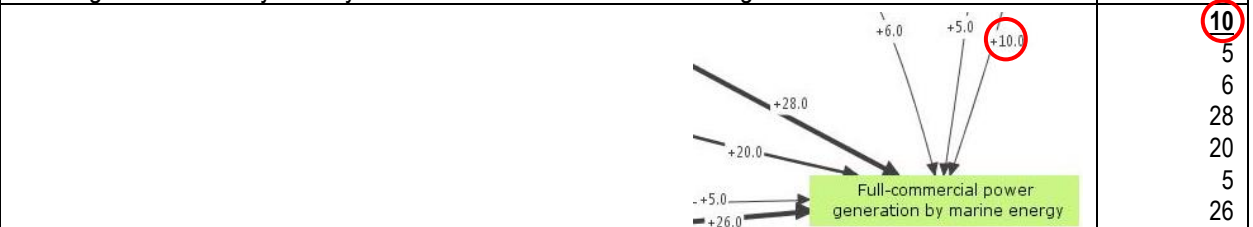
Reduction of number of replies at generic term from 2 to 0 (-100.0%) leads to a total of 24 replies.

	No. of replies	%-value
Focussed support of technology and pilot development	3	13
Development of international standards	2	8
Low ability of developers to work together	2	8
Engagement industry / academia	1	4
Failed demonstrations / technology failures	3	13
Satisfactory technology reliability record	2	8
<b>Showcase commercial-scale projects / successful demonstrators</b>	<b>0</b>	<b>0</b>
Engineering challenge and technology barriers	11	46
Total: 24		

Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:



Impact strength by original model as in Table 12 (#36):  
**45**

Measured value:  
**44**

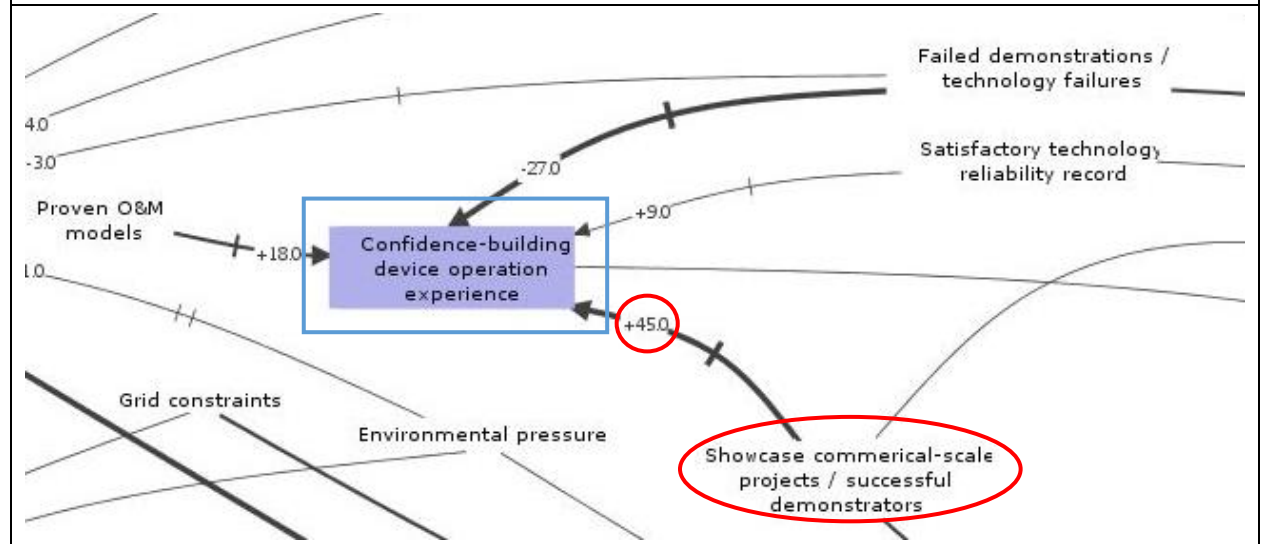
Reduction of impact on final target factor:  
**2%**

## 1.2 Group term: Confidence-building device operation experience

### 1.2.1 Original SD-model

	No. of replies	%-value
Satisfactory technology reliability record	1	9
Failed demonstrations / technology failures	3	27
Proven O&M models	2	18
<b>Showcase commercial-scale projects / successful demonstrators</b>	<b>5</b>	<b>45</b>
	Total: 11	

Drawing section from system dynamics model with focus on examined generic term and examined group term:

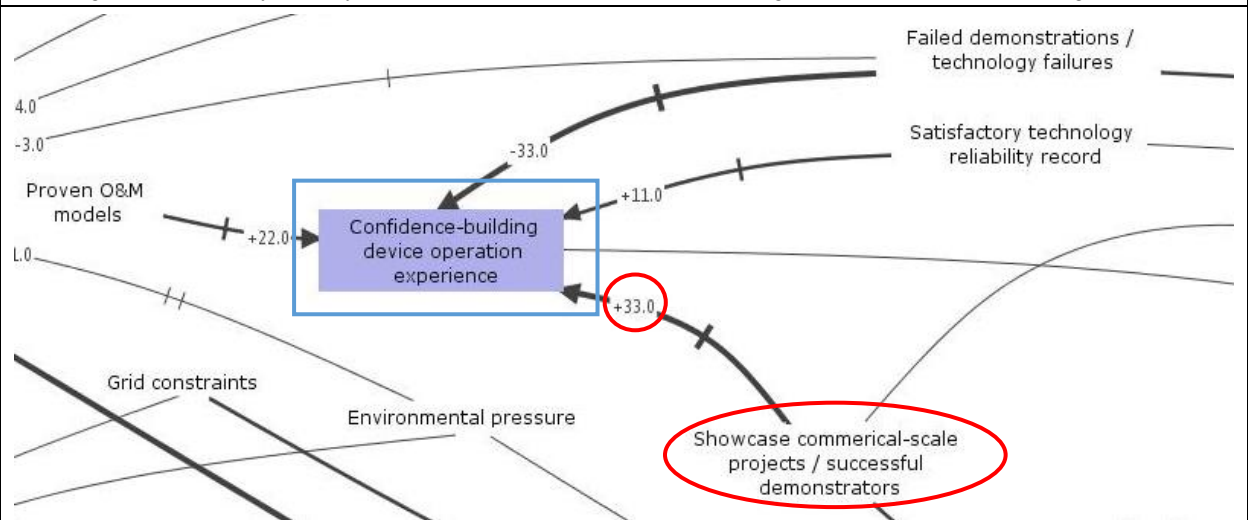


### 1.2.2 Sensitivity analysis “-10% respondents”

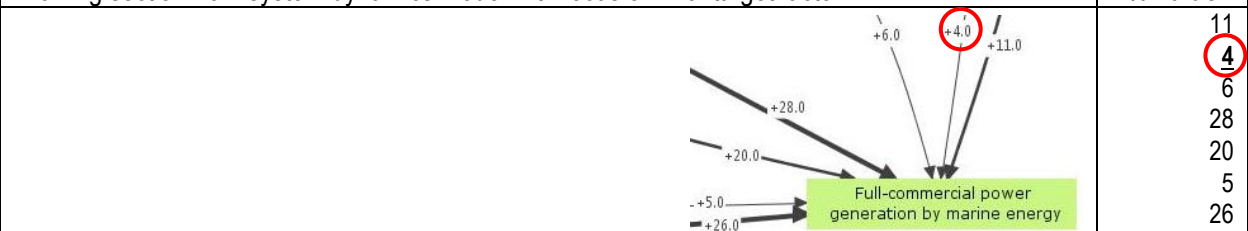
Reduction of number of replies at generic term from 5 to 3 (-40.0%) leads to a total of 9 replies.

	No. of replies	%-value
Satisfactory technology reliability record	1	11
Failed demonstrations / technology failures	3	33
Proven O&M models	2	22
Showcase commercial-scale projects / successful demonstrators	3	33
	Total: 9	

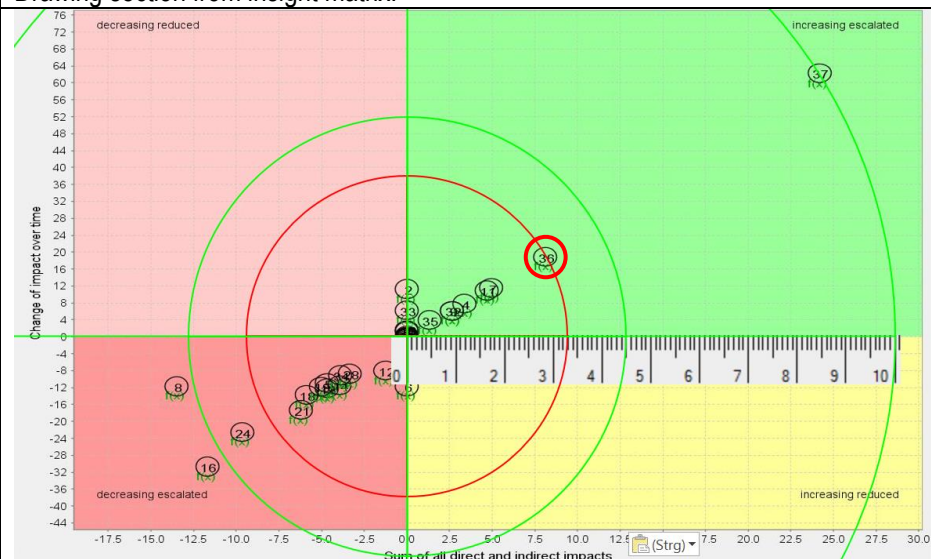
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:



Impact strength by original model as in Table 12 (#36):  
45

Measured value:  
33

Reduction of impact on final target factor:  
36%

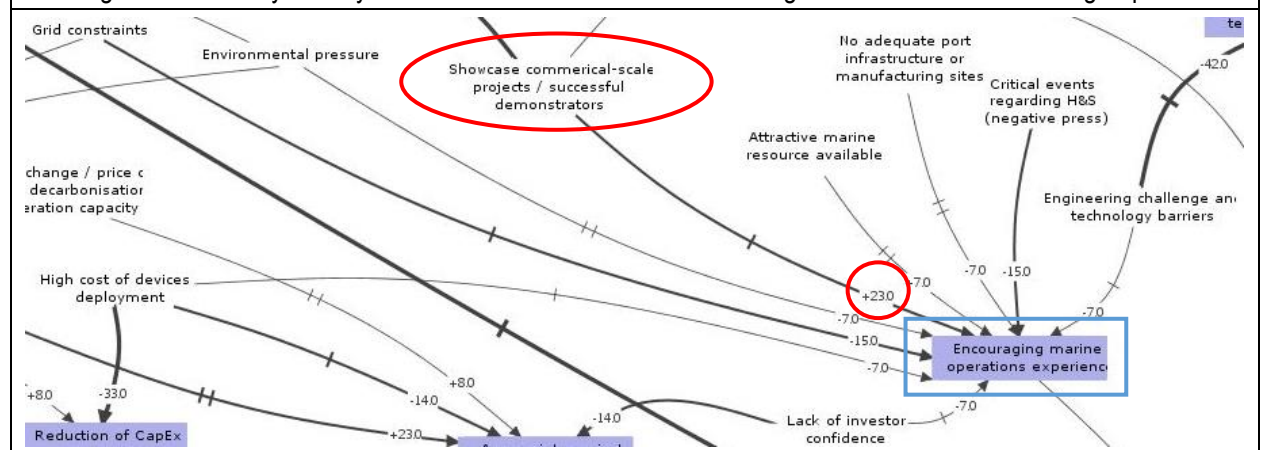


### 1.3 Encouraging marine operations experience

#### 1.3.1 Original SD-model

	No. of replies	%-value
Engineering challenge / technology barriers	1	7
Critical events regarding H&S (negative press)	2	15
No adequate port infrastructure or manufacturing sites	1	7
Attractive marine resource available	1	7
<b>Showcase commercial-scale projects / successful demonstrators</b>	<b>3</b>	<b>23</b>
Environmental pressure	1	7
Grid constraints	2	15
High cost of devices / deployment	1	7
Lack of investor confidence	1	7
Total: 13		

Drawing section from system dynamics model with focus on examined generic term and examined group term:

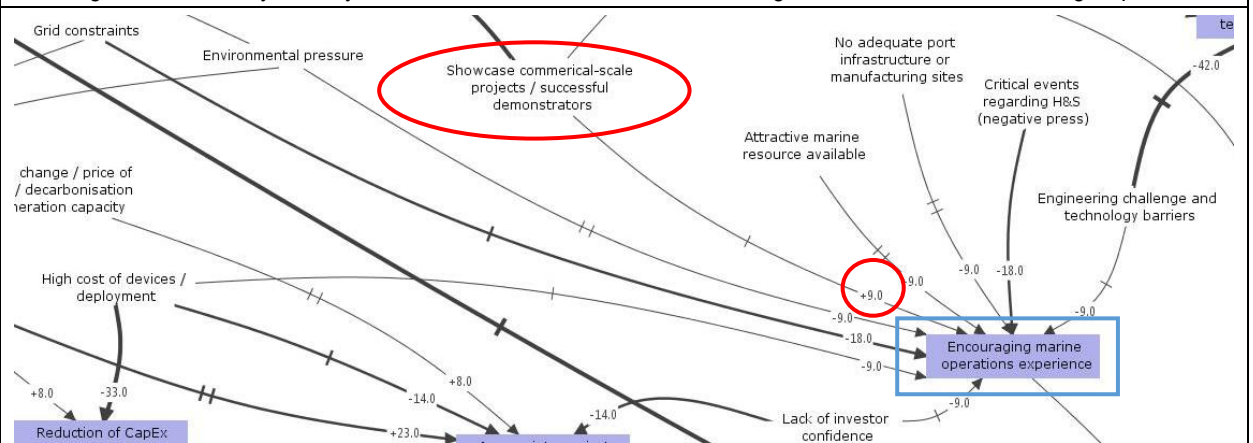


### 1.3.2 Sensitivity analysis “-10% respondents”

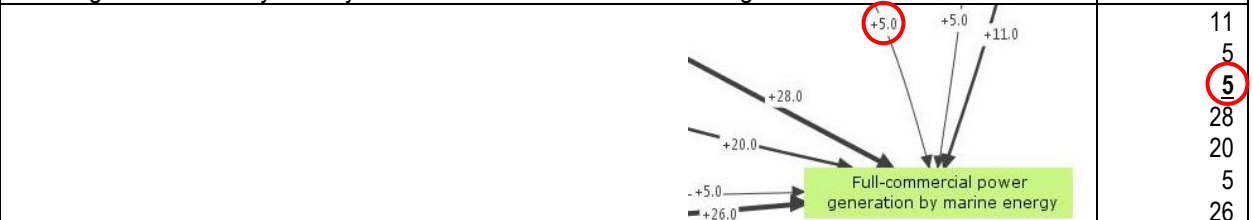
Reduction of number of replies at generic term from 3 to 1 (-66.7%) leads to a total of 11 replies.

	No. of replies	%-value
Engineering challenge / technology barriers	1	9
Critical events regarding H&S (negative press)	2	18
No adequate port infrastructure or manufacturing sites	1	9
Attractive marine resource available	1	9
<b>Showcase commercial-scale projects / successful demonstrators</b>	<b>1</b>	<b>9</b>
Environmental pressure	1	9
Grid constraints	2	18
High cost of devices / deployment	1	9
Lack of investor confidence	1	9
Total: 11		

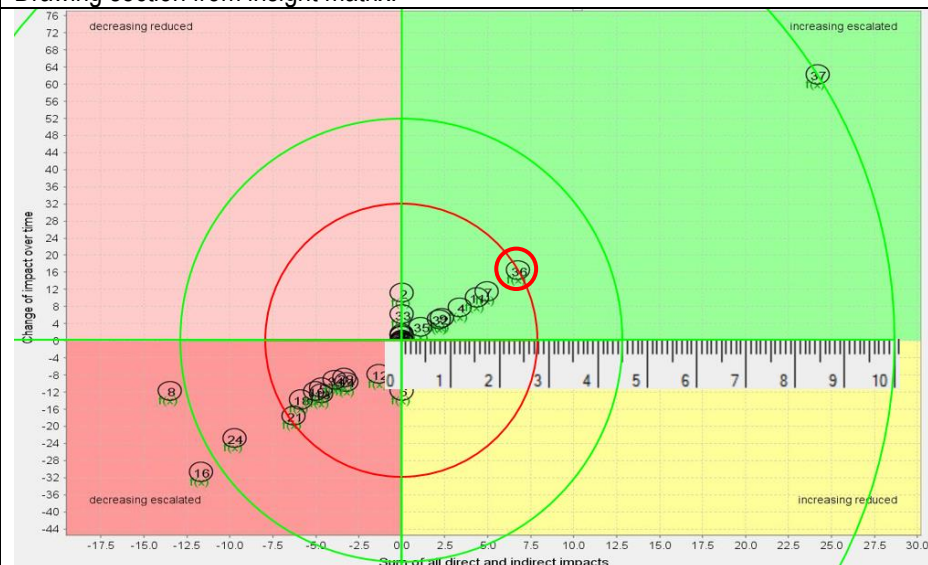
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:



Impact strength by original model as in Table 12 (#36):  
**45**

Measured value:  
**28**

Reduction of impact on final target factor:  
**61%**

Group Term	#	%	Conservative technology learning		Confidence building device operation experience		Encouraging marine operations experience	
			No of replies	%-value	No of replies	%-value	No of replies	%-value
[Consolidated] business development	1	1	2	1		1		1
	2	3	2	2		2		2
	3	4	3	3		3		3
	4	4	3	3		3		3
	5	3	2	2		2		2
	6	1	1	1		1		1
	7	7	5	5		5		5
	8	4	3	3		3		3
	9	10	7	7		7		7
	10	1	1	1		1		1
	11	4	3	3		3		3
	12	12	8	8		8		8
	13	21	14	14		14		14
	14	21	14	14		14		14
[Confidence building device operation experience]	1	99	65	20		65		20
	2	27	3	3		3		3
	3	18	2	2	40.0	2	22	3
	4	45	5	5	Showcase commercial scale projects / successful demonstrators	3	33	10.2
[Conservative technology learning]	1	11	3	13		3		11
	2	7	2	8		2		7
	3	7	2	8		2		7
	4	1	1	1		1		1
	5	23	3	3		3		23
	6	7	2	8		2		7
	7	7	2	8		2		7
	8	42	11	45		11		42
	9	26	11	46		11		26
	10	15	2	2		2		15
	11	1	1	1		1		1
	12	1	1	1		1		1
	13	7	1	1		1		7
	14	7	1	1		1		7
[Encouraging marine operations experience]	1	95	24	10		24		11
	2	7	1	1		1		7
	3	12	1	1		1		12
	4	7	1	1		1		7
	5	23	3	3		3		23
	6	7	1	1		1		7
	7	7	1	1		1		7
	8	42	11	45		11		42
	9	26	11	46		11		26
	10	15	2	2		2		15
	11	1	1	1		1		1
	12	1	1	1		1		1
	13	7	1	1		1		7
	14	7	1	1		1		7
[Appropriate project financing]	1	95	13	6		13		5
	2	14	7	7		7		14
	3	16	7	7		7		16
	4	23	11	11		11		23
	5	8	4	4		4		8
	6	6	3	3		3		6
	7	15	6	6		6		15
	8	15	6	6		6		15
	9	2	1	1		1		2
	10	47	20	20		20		47
	11	13	4	4		4		13
	12	8	1	1		1		8
	13	33	4	4		4		33
	14	8	1	1		1		8
[Reduction of Capex and OpEx]	1	95	47	20		47		20
	2	13	4	4		4		13
	3	33	4	4		4		33
	4	8	1	1		1		8
	5	8	1	1		1		8
	6	8	1	1		1		8
	7	15	9	9		9		15
	8	15	9	9		9		15
	9	2	1	1		1		2
	10	47	20	20		20		47
	11	13	4	4		4		13
	12	8	1	1		1		8
	13	33	4	4		4		33
	14	8	1	1		1		8
[Efficient] consenting, leasing, learning	1	98	12	5		12		5
	2	8	5	5		5		8
	3	6	3	3		3		6
	4	5	3	3		3		5
	5	15	9	9		9		15
	6	15	9	9		9		15
	7	8	5	5		5		8
	8	5	3	3		3		5
	9	6	4	4		4		6
	10	29	26	100		26		29
	11	29	26	100		26		29
	12	11	10	100		10		11
	13	5	5	5		5		5
	14	26	26	100		26		26
[Original After reduction of replies]	1	13	19	19		19		13
	2	8	1	1		1		8
	3	33	4	4		4		33
	4	8	1	1		1		8
	5	8	1	1		1		8
	6	8	1	1		1		8
	7	15	9	9		9		15
	8	15	9	9		9		15
	9	2	1	1		1		2
	10	47	20	20		20		47
	11	13	4	4		4		13
	12	8	1	1		1		8
	13	33	4	4		4		33
	14	8	1	1		1		8
[Original After reduction of replies]	1	98	12	5		12		45
	2	8	5	5		5		28
	3	5	3	3		3		
	4	5	3	3		3		
	5	15	9	9		9		
	6	15	9	9		9		
	7	8	5	5		5		
	8	5	3	3		3		
	9	6	4	4		4		
	10	29	26	100		26		
	11	29	26	100		26		
	12	11	10	100		10		
	13	5	5	5				

**E            System dynamics computer models**

**E.1        Model 1: Full-commercial power generation by marine energy**

**E.1.4      Sensitivity and robustness**

**E.1.4.2    Removal of subsets of sample population**

**E.1.4.2.2 Lack of investor confidence**

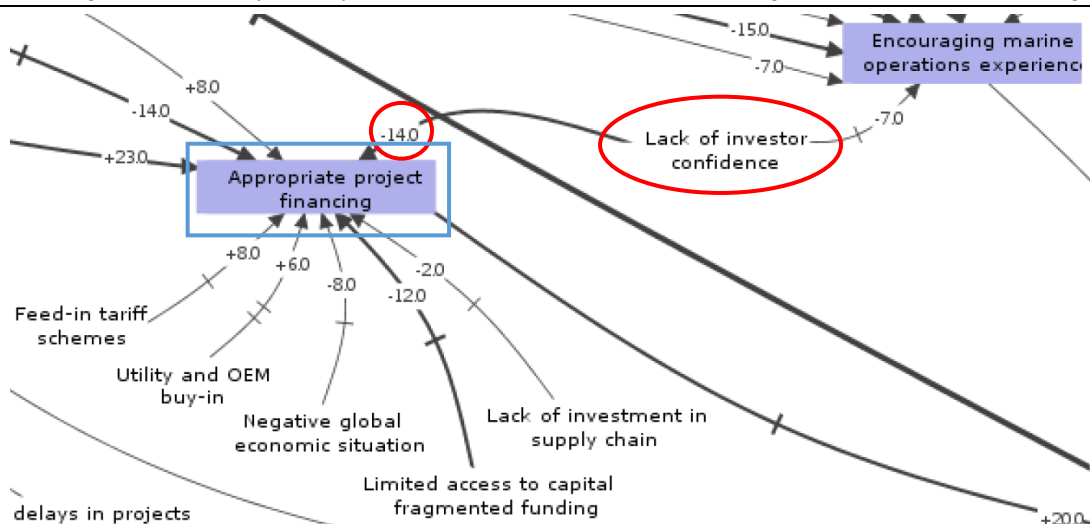
## 2 Generic term: Lack of investor confidence (#24)

### 2.1 Group term: Appropriate project financing

#### 2.1.1 Original SD-model

	No. of replies	%-value
<b>Lack of investor confidence</b>	7	14
Climate change / price of carbon / decarbonisation of generation capacity	4	8
High cost of devices / deployment	7	14
Strong and long-term commitment from government	11	23
Feed-in tariff schemes	4	8
Utility and OEM buy-in	3	6
Negative global economic situation	4	8
Limited access to capital / fragmented funding	6	12
Lack of investment in supply chain	1	2
Total:	47	

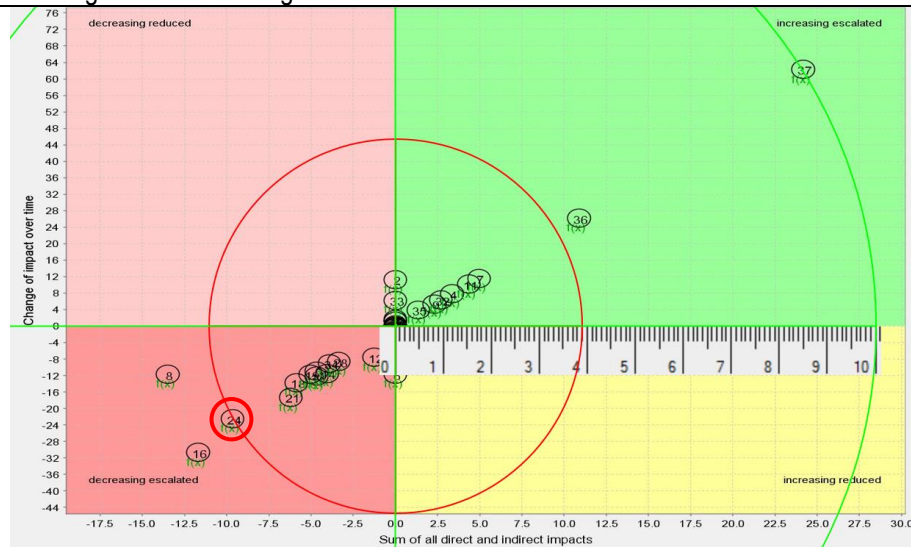
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:

	%-value
Full-commercial power generation by marine energy	11
	5
	6
	28
	20
	5
	26

Drawing section from insight matrix:



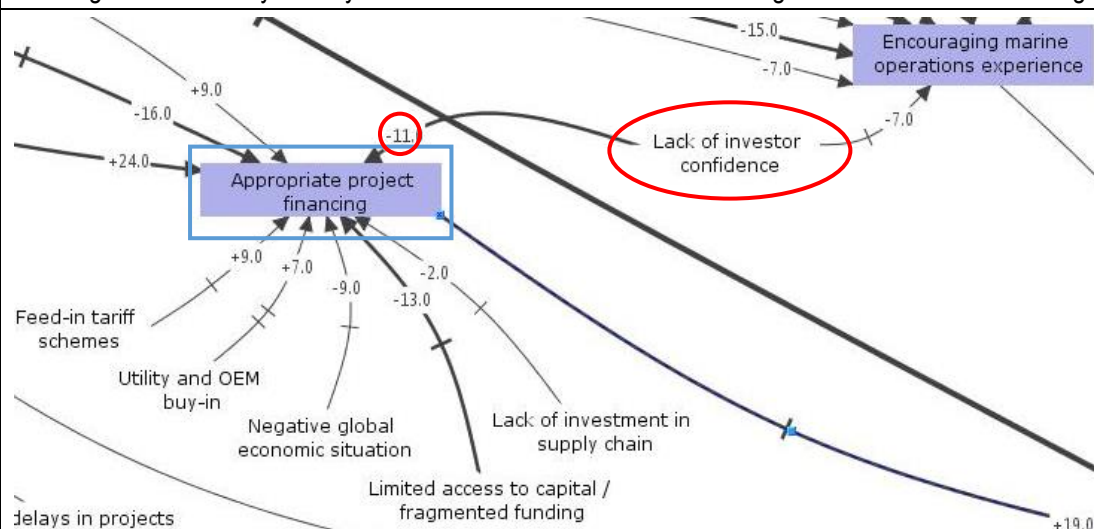
Impact strength by original model as in Table 12 (#24):  
39

### 2.1.2 Sensitivity analysis “-10% respondents”

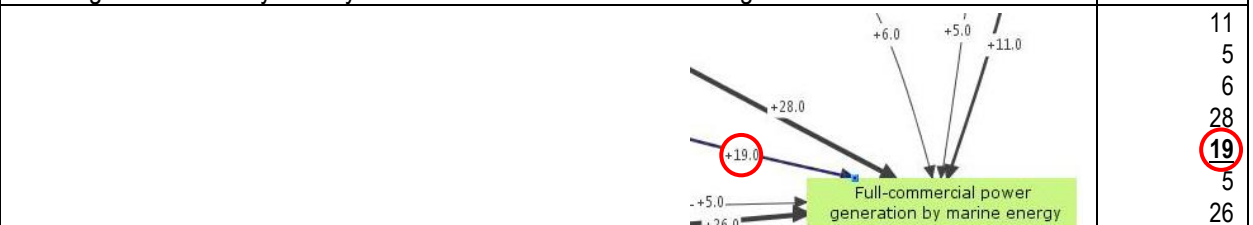
Reduction of number of replies at generic term from 7 to 5 (-28.6%) leads to a total of 45 replies.

	No. of replies	%-value
<b>Lack of investor confidence</b>	5	11
Climate change / price of carbon / decarbonisation of generation capacity	4	9
High cost of devices / deployment	7	16
Strong and long-term commitment from government	11	24
Feed-in tariff schemes	4	9
Utility and OEM buy-in	3	7
Negative global economic situation	4	9
Limited access to capital / fragmented funding	6	13
Lack of investment in supply chain	1	2
Total: 45		

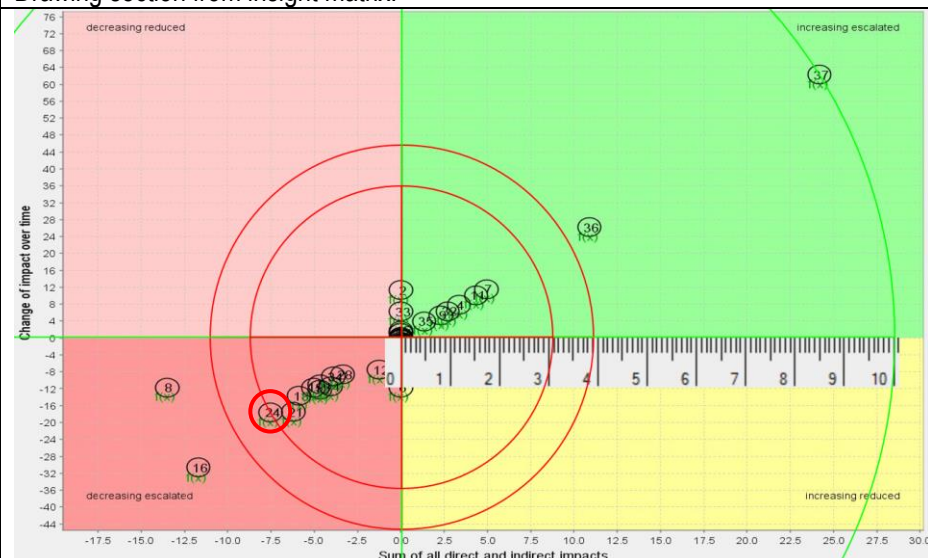
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:



Impact strength by original model as in Table 12 (#24):  
39

Measured value:  
31

Reduction of impact on final target factor:  
26%

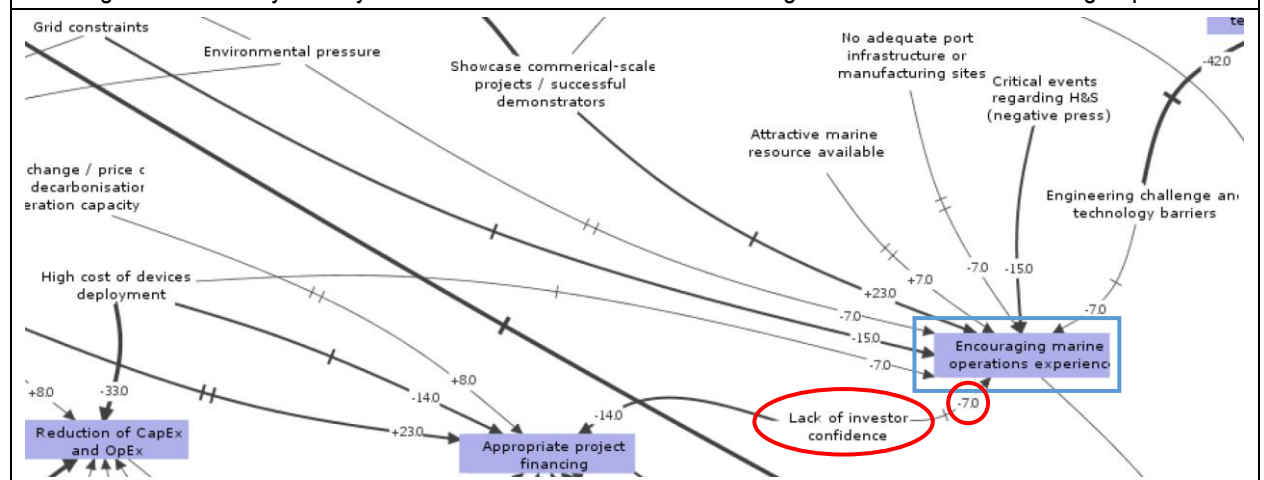


## 2.2 Group term: Encouraging marine operations experience

### 2.2.1 Original SD-model

	No. of replies	%-value
Engineering challenge / technology barriers	1	7
Critical events regarding H&S (negative press)	2	15
No adequate port infrastructure or manufacturing sites	1	7
Attractive marine resource available	1	7
Showcase com.-scale projects / successful demonstrators	3	23
Environmental pressure	1	7
Grid constraints	2	15
High cost of devices / deployment	1	7
<b>Lack of investor confidence</b>	<b>1</b>	<b>7</b>
	Total: 13	

Drawing section from system dynamics model with focus on examined generic term and examined group term:

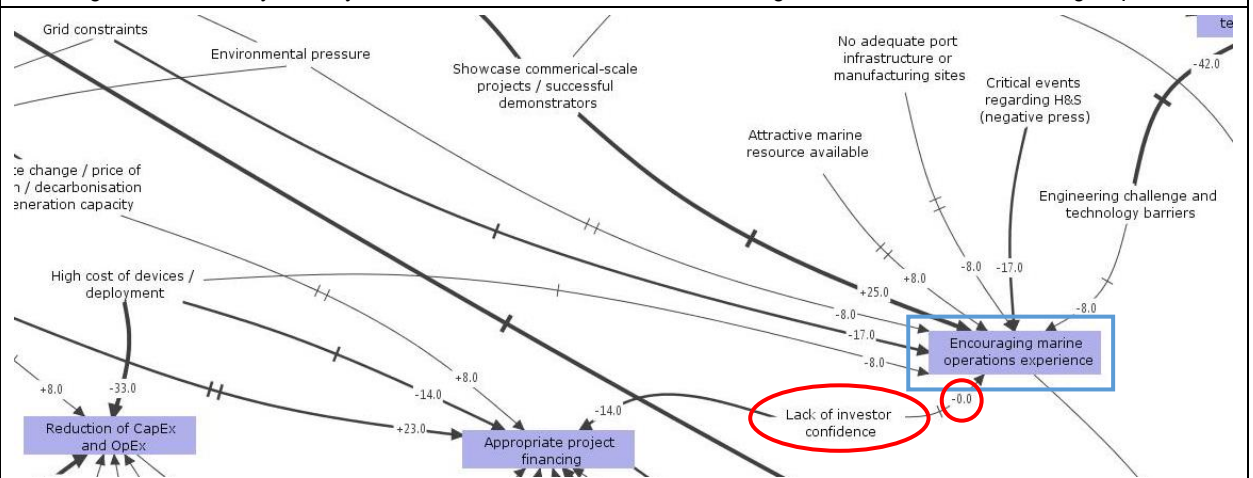


## 2.2.2 Sensitivity analysis “-10% respondents”

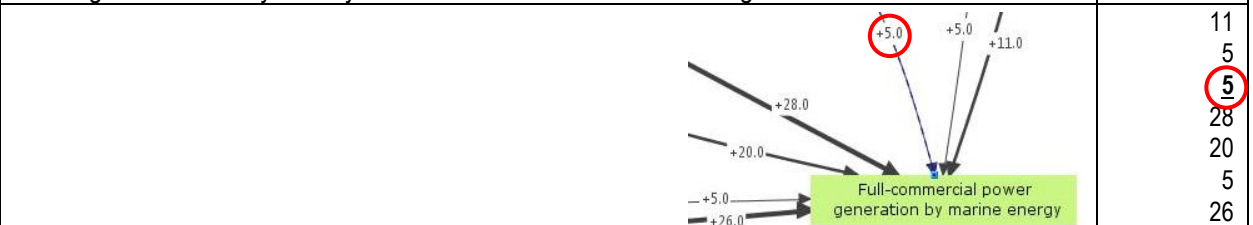
Reduction of number of replies at generic term from 1 to 0 (-100.0%) leads to a total of 12 replies.

	No. of replies	%-value
Engineering challenge / technology barriers	1	8
Critical events regarding H&S (negative press)	2	17
No adequate port infrastructure or manufacturing sites	1	8
Attractive marine resource available	1	8
Showcase com.-scale projects / successful demonstrators	3	25
Environmental pressure	1	8
Grid constraints	2	17
High cost of devices / deployment	1	8
<b>Lack of investor confidence</b>	<b>0</b>	<b>0</b>
	Total: 12	

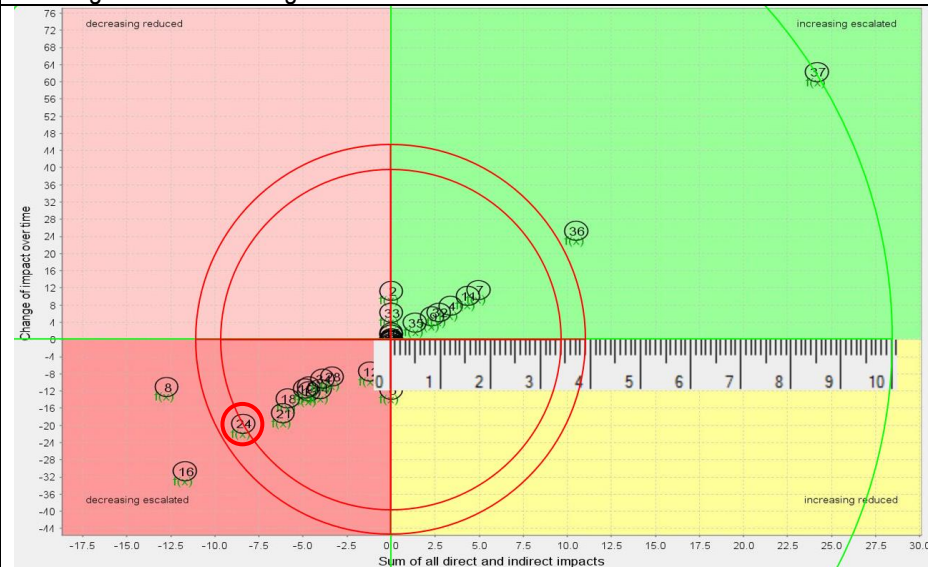
Drawing section from system dynamics model with focus on examined generic term and examined group term:



Drawing section from system dynamics model with focus on final target factor:



Drawing section from insight matrix:



Impact strength by original model as in Table 12 (#24):  
**39**

Measured value:  
**34**

Reduction of impact on final target factor:  
**15%**



Group Term	#	%	No of replies	(Appropriate) project financing		(Encouraging) marine operations experience	
				No of replies	%-value	No of replies	%-value
(Consolidated) business development	1	1	1				
	2	3	2				
	3	4	3				
	4	4	3				
	5	3	2				
	6	1	1				
	7	7	5				
	8	4	3				
	9	10	7				
	10	1	1				
	11	4	3				
	12	12	8				
	13	21	14				
	14	21	14				
(Confidence-building device operation experience)	15	12	12				
	16	19	65	26	28	45	28
	17	9	3				
	18	2	2				
	19	3	3				
	20	2	2				
	21	4	5				
	22	45	5				
	23	99	11	5		11	5
	24	1	11	3	12		
	25	7	2				
	26	7	2				
	27	7	2				
	28	4	1				
(Consecutive) technology learning	29	1	1				
	30	1	1				
	31	7	2				
	32	2	2				
	33	4	3				
	34	1	1				
	35	1	1				
	36	1	1				
	37	1	1				
	38	1	1				
	39	1	1				
	40	1	1				
	41	1	1				
	42	1	1				
(Encouraging) marine operations experience	43	8	42	11	42		
	44	11	11				
	45	26	26	100	11	26	11
	46	1	1				
	47	2	2				
	48	2	2				
	49	1	1				
	50	1	1				
	51	1	1				
	52	1	1				
	53	1	1				
	54	1	1				
	55	1	1				
	56	1	1				
(Appropriate) project financing	57	95	13	6			
	58	1	14	7			
	59	2	8	4			
	60	3	14	7			
	61	4	23	11			
	62	5	8	4			
	63	6	6	3			
	64	7	8	4			
	65	8	12	6			
	66	9	2	1			
	67	9	7	1			
	68	9	7	1			
	69	9	7	1			
	70	9	7	1			
Reduction of CapEx and OpEx	71	33	4				
	72	8	1				
	73	3	3	4			
	74	4	8	1			
	75	5	8	1			
	76	6	8	1			
	77	6	8	1			
	78	6	8	1			
	79	6	8	1			
	80	6	8	1			
	81	6	8	1			
	82	6	8	1			
	83	6	8	1			
	84	6	8	1			
(Efficient) consenting, leasing, licensing	85	95	47	20			
	86	1	33	4			
	87	2	8	1			
	88	3	3	4			
	89	4	8	1			
	90	5	8	1			
	91	6	8	1			
	92	6	8	1			
	93	6	8	1			
	94	6	8	1			
	95	6	8	1			
	96	6	8	1			
	97	6	8	1			
	98	6	8	1			
	99	99	12	5			
	100	1	3	19			
	101	2	6	4			
	102	3	6	4			
	103	4	3	2			
	104	5	15	9			
	105	6	15	9			
	106	7	8	5			
	107	8	5	3			
	108	9	6	4			
	109	60	26				
	110	234	100	232			
	111						
	112						
	113						
	114						
	115						
	116						
	117						
	118						
	119						
	120						
	121						
	122						
	123						
	124						
	125						
	126						
	127						
	128						
	129						
	130						
	131						
	132						
	133						
	134						
	135						
	136						
	137						
	138						
	139						
	140						
	141						
	142						
	143						
	144						
	145						
	146						
	147						
	148						
	149						
	150						
	151						
	152						
	153						
	154						
	155						
	156						
	157						
	158						
	159						
	160						
	161						
	162						
	163						
	164						
	165						
	166						
	167						
	168						
	169						
	170						
	171						
	172						
	173						
	174						
	175						
	176						
	177						
	178						
	179						
	180						
	181						
	182						
	183						
	184						
	185						
	186						
	187						
	188						
	189						
	190						
	191						
	192						
	193						
	194						
	195						
	196						
	197						
	198						
	199						
	200						
	201						
	202						
	203						
	204						
	205						
	206						
	207						
	208						
	209						
	210						
	211						
	212						
	213						
	214						
	215						
	216						
	217						
	218						
	219						
	220						
	221						
	222						
	223						
	224						
	225						
	226						
	227						
	228						
	229						
	230						
	231						
	232						
	233						
	234						
	235						
	236						
	237						
	238						
	239						
	240						
	241						
	242						
	243						
	244						
	245						
	246						
	247						
	248						
	249						

**E            System dynamics computer models**

**E.1        Model 1: Full-commercial power generation by marine energy**

**E.1.4      Sensitivity and robustness**

**E.1.4.3    Removal of one category of stakeholder**

**E.1.4.3.1 Configuration table**

5		Marine operations experience				6
<b>25 Positive (supporting/accelerating)</b>		<b>4</b>	<b>INT</b>	<b>DEL</b>	<b>2</b>	<b>0,36</b>
98		1	0,09	I	Attractive marine resource available	
		3	0,27	m	Showcase commercial-scale projects / successful demonstrators	
<b>34 Negative (hindering/delaying)</b>		<b>7</b>	<b>INT</b>		<b>7</b>	<b>0,63</b>
100		1	0,09	I	No adequate port infrastructure or manufacturing sites	
		1	0,09	m	High cost of devices / deployment	
		1	0,09	s	Critical events regarding H&S (negative press)	
		0		I		
		1	0,09	m	Lack of investor confidence	
		1	0,09	m	Engineering challenge and technology barriers	
		2	0,18	m	Grid constraints	
Total						
59						
198						
						<b>0,99</b>

5		Device operation experience				5
<b>25 Positive (supporting/accelerating)</b>		<b>7</b>	<b>INT</b>	<b>DEL</b>	<b>3</b>	<b>0,70</b>
98		2	0,20	m	Proven O&M models	
		5	0,50	m	Showcase commercial-scale projects / successful demonstrators	
		0		m		
<b>34 Negative (hindering/delaying)</b>		<b>3</b>	<b>INT</b>		<b>1</b>	<b>0,30</b>
100						
Total		3	0,30	m	Failed demonstrations / technology failures	
59						
198						
						<b>1</b>

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW Q5 EVALUATION replies 234 - removal 10 dev man / 5C - 10.07.2017 - 19:48 Page 3 of 7

Ralf Bucher      p-20130406-bucher-post-viva-INTERVIEW Q5 EVALUATION replies 234 - removal 10 dev man / 5C - 10.07.2017 - 19:48      Page 4 of 7

5		Reduction of CapEx and OpEx				6
<b>25 Positive (supporting/accelerating)</b>		<b>4</b>	<b>INT</b>	<b>DEL</b>	<b>2</b>	<b>0,36</b>
98		1	0,09	m	Strong and long-term commitment from government	
		3	0,27	s	Cost-effective way to harvest marine energy	
<b>34 Negative (hindering/delaying)</b>		<b>7</b>	<b>INT</b>		<b>4</b>	<b>0,63</b>
100		1	0,09	m	Early commercial pressure	
		4	0,36	s	High cost of devices / deployment	
		1	0,09	l	Hidden subsidies in other renewables	
		1	0,09	l	Long delays of projects coming on line	
<b>Total</b>						
59						
198						
						<b>0,99</b>

5		Technology learning				11
<b>25 Positive (supporting/accelerating)</b>		<b>9</b>	<b>INT</b>	<b>DEL</b>	<b>5</b>	<b>0,39</b>
98		2	0,09	s	Development of international standards	
		1	0,04	m	Showcase commercial-scale projects / successful demonstrators	
		2	0,09	m	Satisfactory technology reliability record	
		3	0,13	m	Focussed support of technology development and pilot development	
		1	0,04	s	Engagement industry/academia	
<b>34 Negative (hindering/delaying)</b>		<b>13</b>	<b>INT</b>		<b>3</b>	<b>0,58</b>
100						
<b>Total</b>		<b>3</b>	<b>0,13</b>	<b>m</b>	<b>Failed demonstrations / technology failures</b>	
59						
198						
						<b>0,97</b>

Ralf Bucher p-20130406-bucher-post-viva-INTERVIEW\_Q5\_EVALUATION\_replies\_234 - removal 10 dev man / 5C - 10.07.2017 - 19:48 Page 7 of 7

**E            System dynamics computer models**

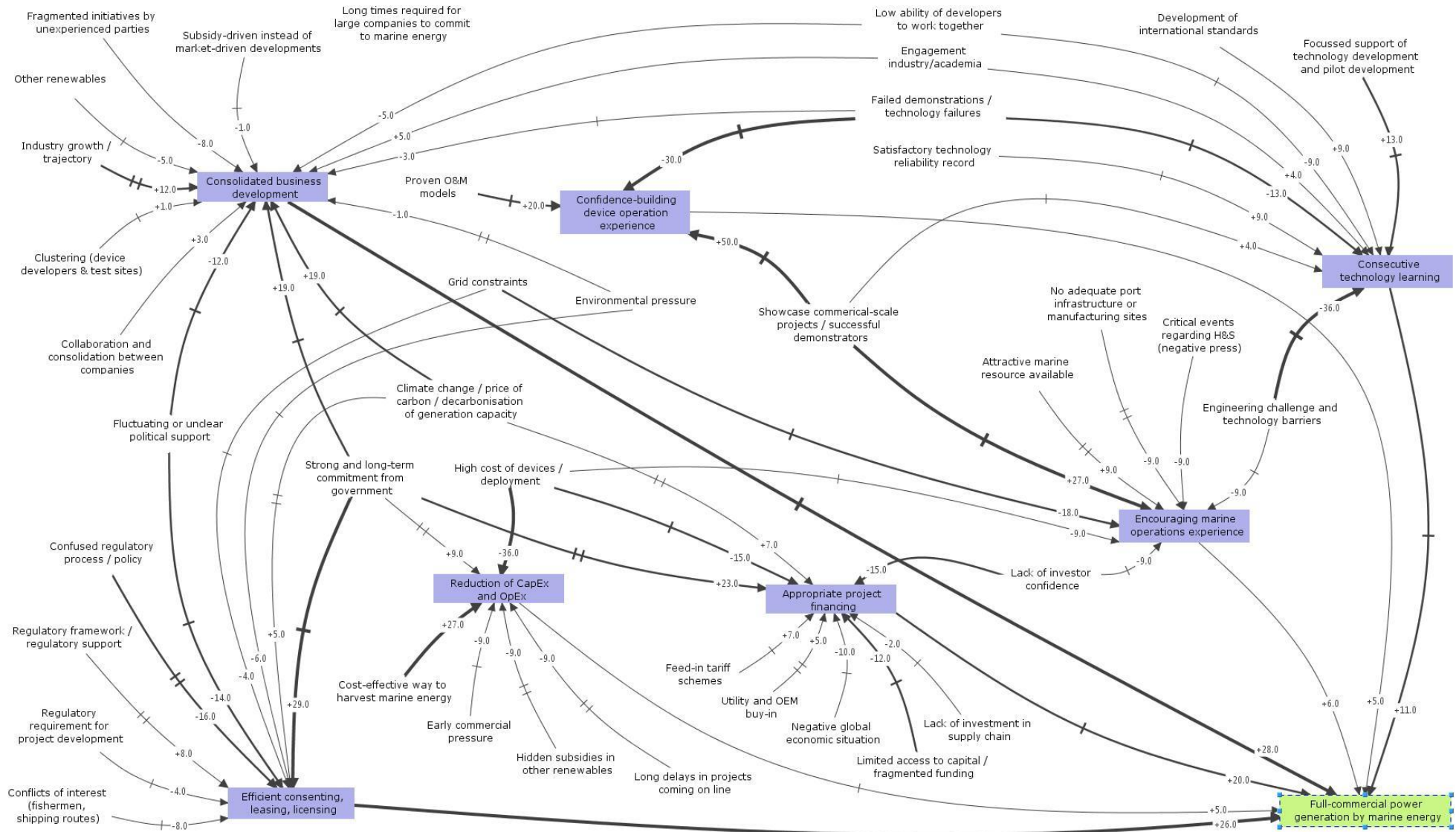
**E.1        Model 1: Full-commercial power generation by marine energy**

**E.1.4      Sensitivity and robustness**

**E.1.4.3    Removal of one category of stakeholder**

**E.1.4.3.2 Causal diagram**

# Model 1 (basic): Full-commercial power generation by marine energy (sensitivity analysis / without stakeholder group “device manufacturers”)





**E            System dynamics computer models**

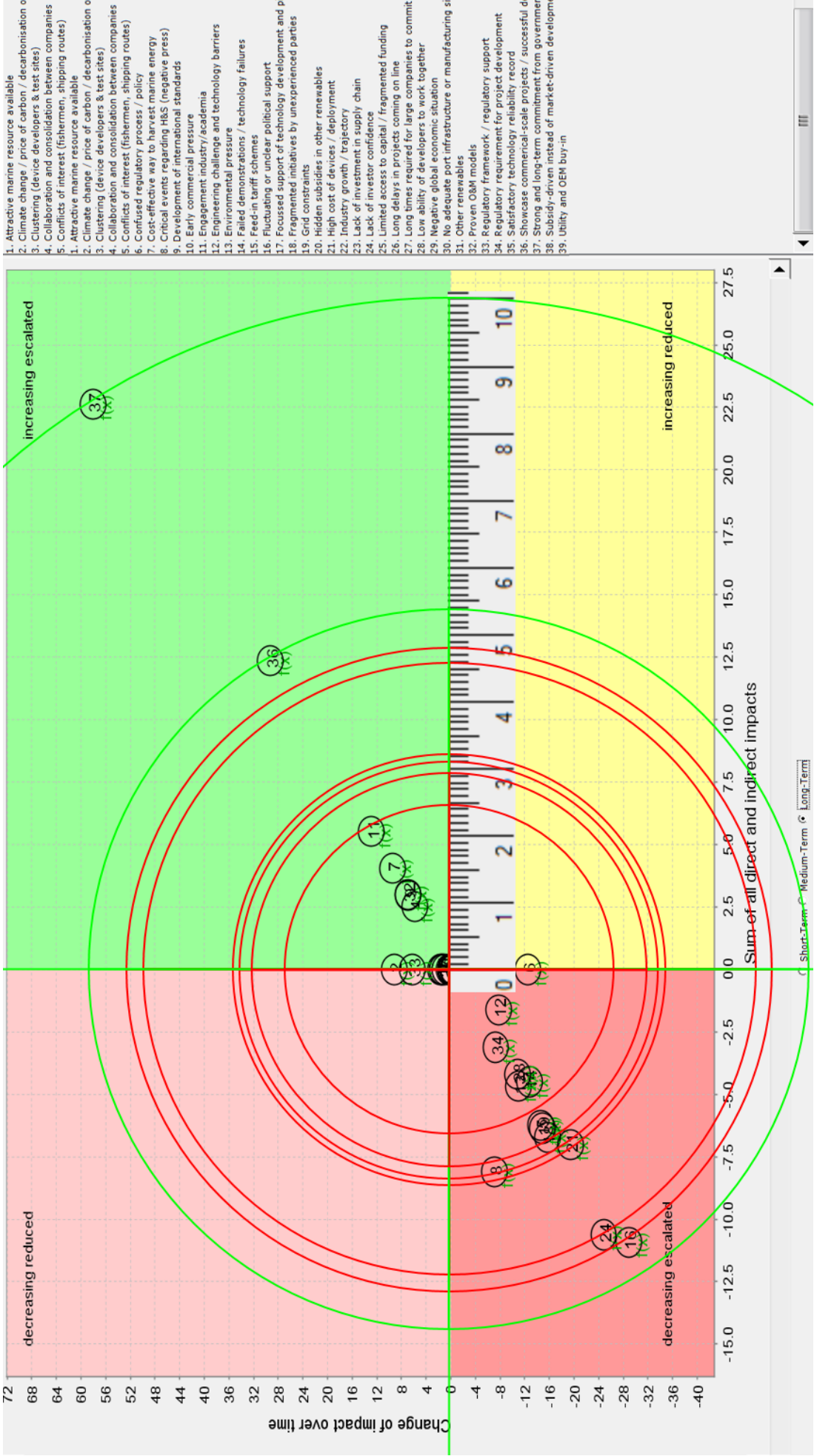
**E.1        Model 1: Full-commercial power generation by marine energy**

**E.1.4      Sensitivity and robustness**

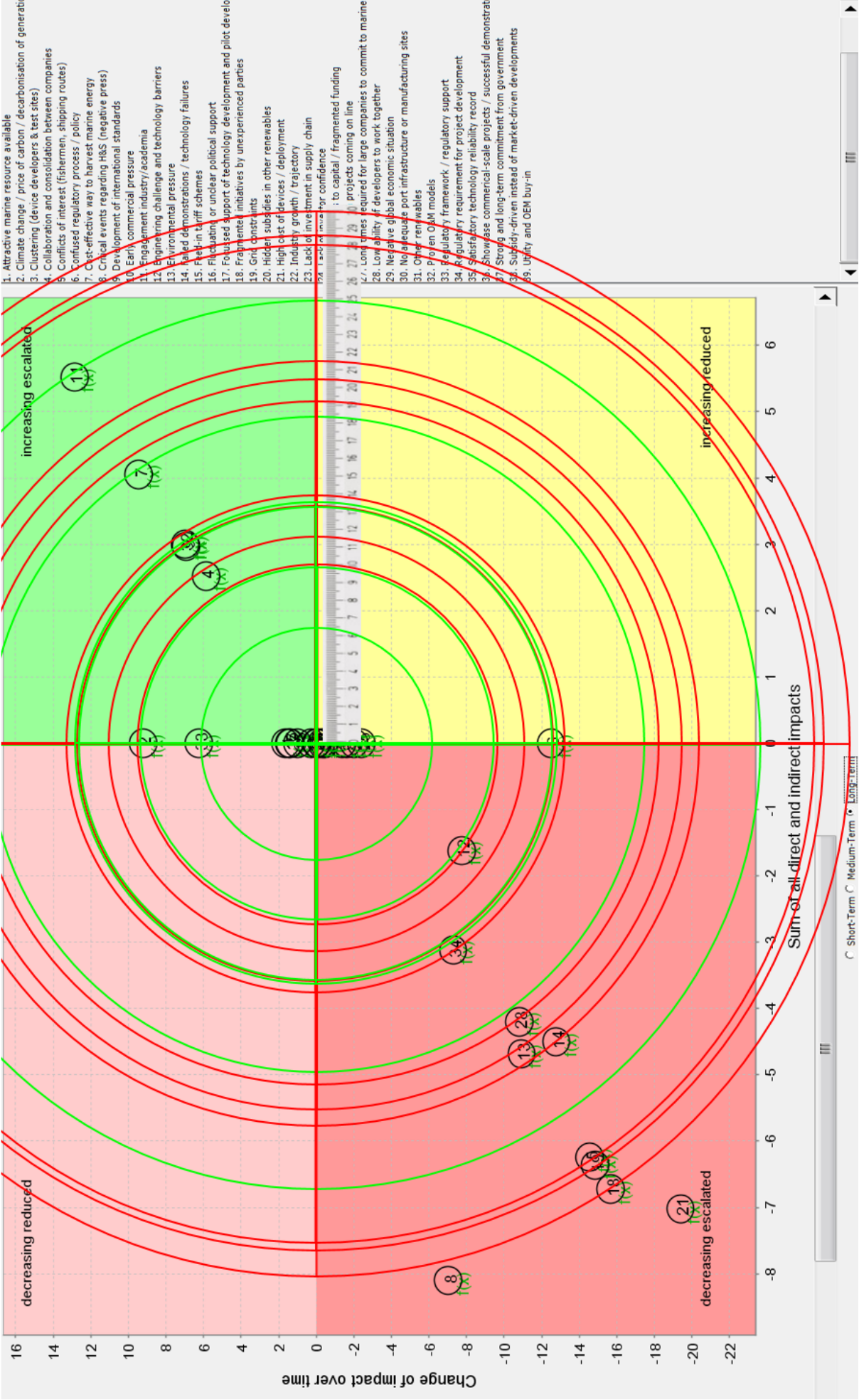
**E.1.4.3    Removal of one category of stakeholder**

**E.1.4.3.3 Insight matrix**

Model 1 (basic): Full-commercial power generation by marine energy



Model 1 (basic): Full-commercial power generation by marine energy



- E            System dynamics computer models**
- E.1        Model 1: Full-commercial power generation by marine energy**
- E.1.4      Sensitivity and robustness**
- E.1.4.3    Removal of one category of stakeholder**
- E.1.4.3.4 Ranking of impact factors and determination of milestones**

## 1 Ranking of impact factors

In the following table, the effect on the ranking of individual generic terms are displayed:

Generic term	Ranking				Change	Trend
	Original		Modified		Ranking [abs.]	↔ remain
	% normalised	Rank number	% normalised	Rank number		↑ higher  ↓ lower
Reinforcing						
Strong and long-term commitment from government (#37)	100	1	100	1	0	↔
Showcase commercial-scale projects / (...) demonstrators (#36)	45	2	54	2	9	↑↑
Cost-effective way to harvest marine energy (#7)	20	3	18	4	-2	↓
Engagement industry / academia (#11)	17	4	25	3	8	↑↑
Collaboration and consolidation between companies (#4)	13	5	11	7	-2	↓
Proven O&M models (#32)	11	6	14	5	3	↑
Climate change / price of carbon / decarbonisation (#2)	10	7	10	8	0	↔
Development of internat. standards (#9)	9	8	13	6	4	↑
Satisfactory technology reliability record (#35)	6	9	2	10	-4	↓
Regulatory framework / regulatory support (#33)	5	10	6	9	1	↑
Countervailing						
Fluctuating or unclear political support (#16)	49	1	48	1	-1	↓
Critical events regarding H&S (negative press) (#8)	48	2	31	4	-17	↓↓↓↓
Lack of investor confidence (#24)	39	3	46	2	7	↑↑
High cost of devices / deployment (#21)	26	4	32	3	6	↑↑
Fragmented initiatives by unexperienced parties (#18)	23	5	30	5	7	↑↑
Grid constraints (#19)	20	6	29	6	9	↑↑
Environmental pressure (#13)	19	7	20	9	1	↑
Conflicts of interest (#5)	18	8	28	7	10	↑↑↑
Failed demonstrations / technology failures (#14)	17	9	22	8	5	↑↑
Regulatory requirement for project development (#34)	15	10	14	11	-1	↓
Low ability of developers to work together (#28)	14	11	19	10	5	↑↑
Confused regulatory process / policy (#6)	10	12	13	12	3	↑
Engineering challenge / technology barriers (#12)	8	13	10	13	2	↑

## 2 Sensitivity analysis “removal of one category of stakeholders”

In the following table, the effect on the ranking of the 3 defined milestones are displayed:

	Impact strength on final target: original		Impact strength on final target: without "device manufacturers"			Change
	% normalised	% per milestone	% normalised	% per generic term	% per milestone	
+ Strong and long-term commitment from government	100		100	0		
– Fluctuating or unclear political support	49		48	-1		
– Grid constraints	20		29	9		
– Environmental pressure	19		20	1		
+ Engagement industry / academia	17		25	8		
– Conflicts of interest	18		28	10		
+ Regulatory framework / regulatory support	5		6	1		
– Regulatory requirement for project development	15		14	-1		
– Confused regulatory process / policy	10		13	3		
+ Climate change / price of carbon / decarbonisation	10		10	0		
<b>Milestone No. 1: "Governmental support"</b>	<b>263</b>	<b>48,5</b>	<b>293</b>		<b>49,2</b>	<b>0,72</b>
+ Showcase commercial-scale projects / (...) demonstrators	45		54	9		
– Fragmented initiatives by unexperienced parties	23		30	7		
– Critical events regarding H&S (negative press)	48		31	-17		
– Failed demonstrations / technology failures	17		22	5		
– Low ability of developers to work together	14		19	5		
+ Collaboration and consolidation between companies	13		11	-2		
+ Satisfactory technology reliability record	6		2	-4		
– Engineering challenge / technology barriers	8		10	2		
+ Development of international standards	9		13	4		
<b>Milestone No. 2: "Array-scale succes"</b>	<b>183</b>	<b>33,8</b>	<b>192</b>		<b>32,3</b>	<b>-1,49</b>
– Lack of investor confidence	39		46	7		
– High cost of devices / deployment	26		32	6		
+ Cost-effective way to harvest marine energy	20		18	-2		
+ Proven O&M models	11		14	3		
<b>Milestone No. 3: "Cost reduction"</b>	<b>96</b>	<b>17,7</b>	<b>110</b>		<b>18,5</b>	<b>0,78</b>
<b>Total</b>	<b>542</b>	<b>100,0</b>	<b>595</b>		<b>100,0</b>	<b>0,0</b>

**E            System dynamics computer models**

**E.1          Model 1: Full-commercial power generation by marine energy**

**E.1.4       Sensitivity and robustness**

**E.1.4.4     Impact by determination of time behaviour**

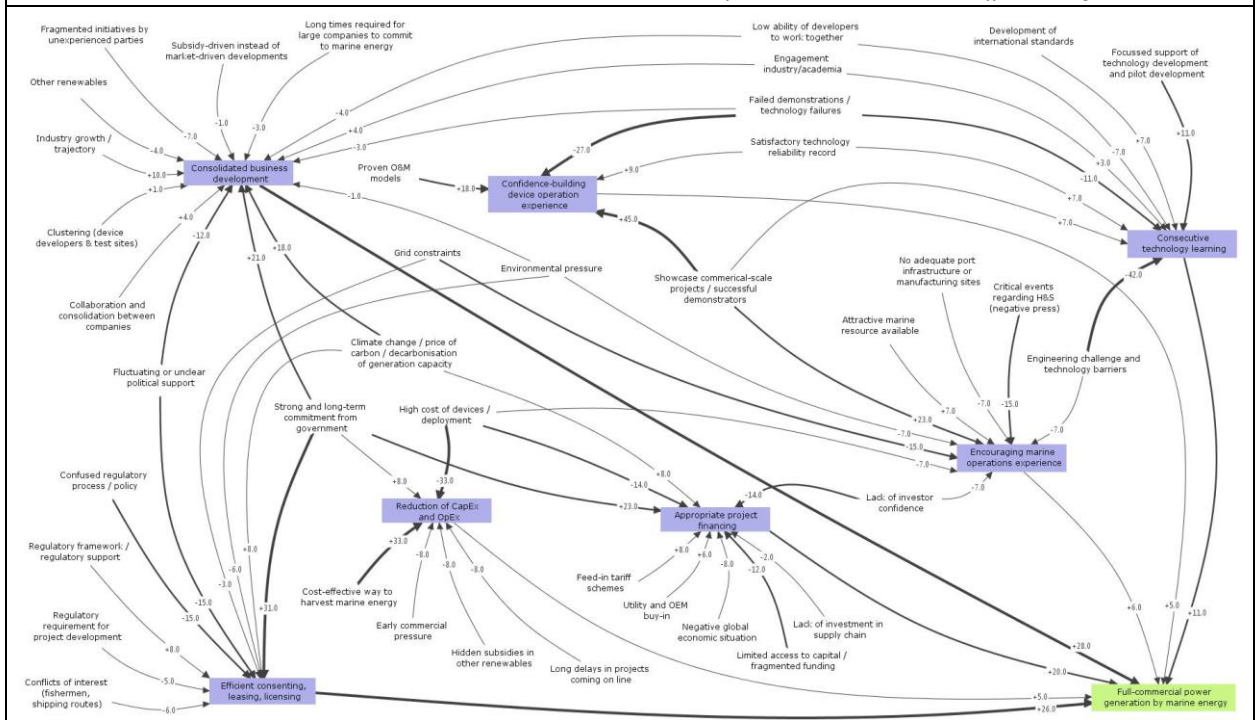
**E.1.4.4.1   No time delays**



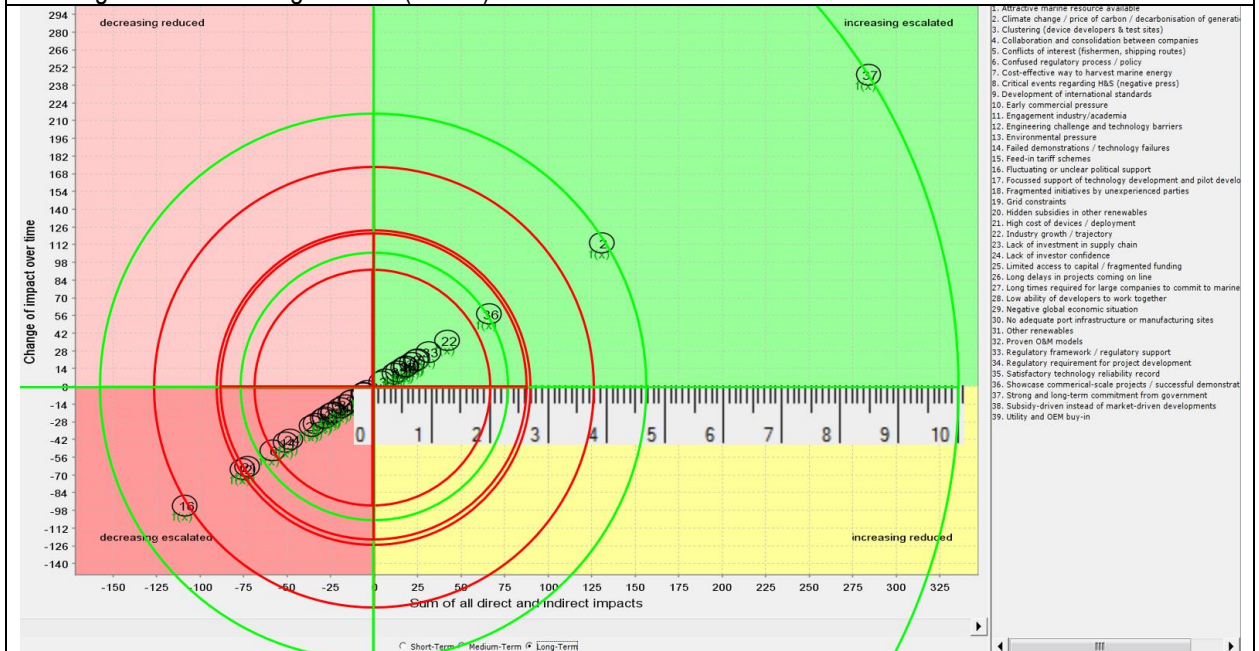
# 1 Ranking of Generic Terms: Interview Replies and Model without Time Impact Definition

## 1.1 System Dynamics Model

SD-model without time correlations: deletion of --- for short-term, -|- for medium-term and -||- for long-term:



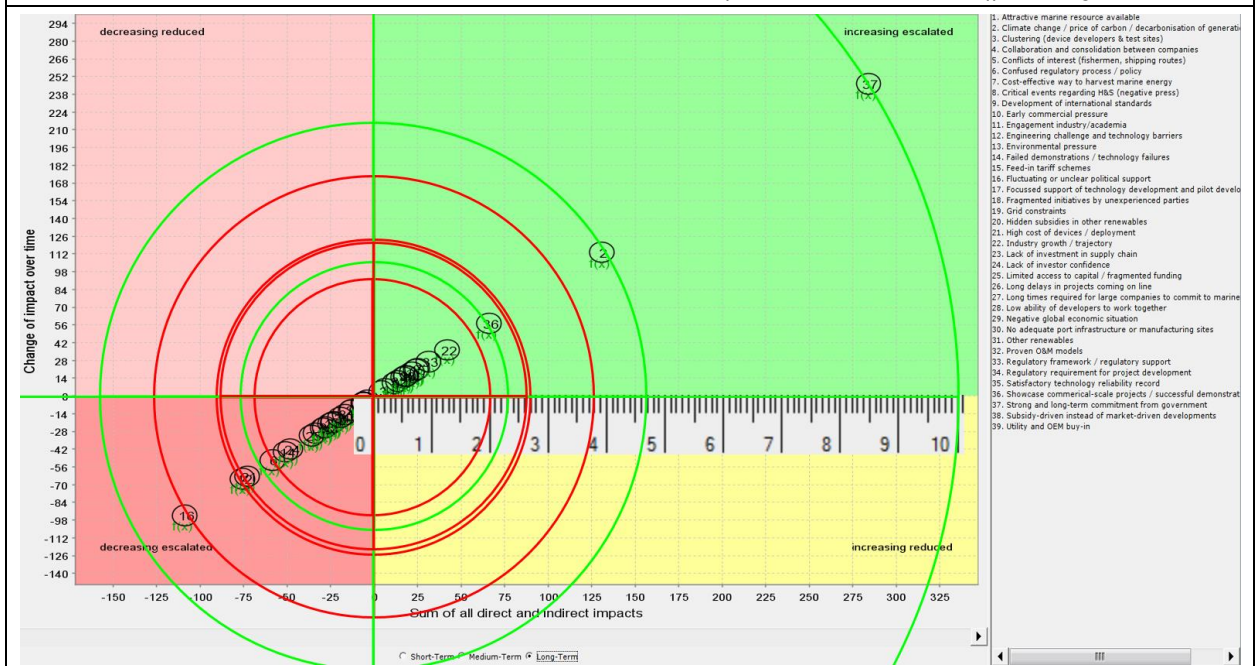
Drawing section from insight matrix (overall):



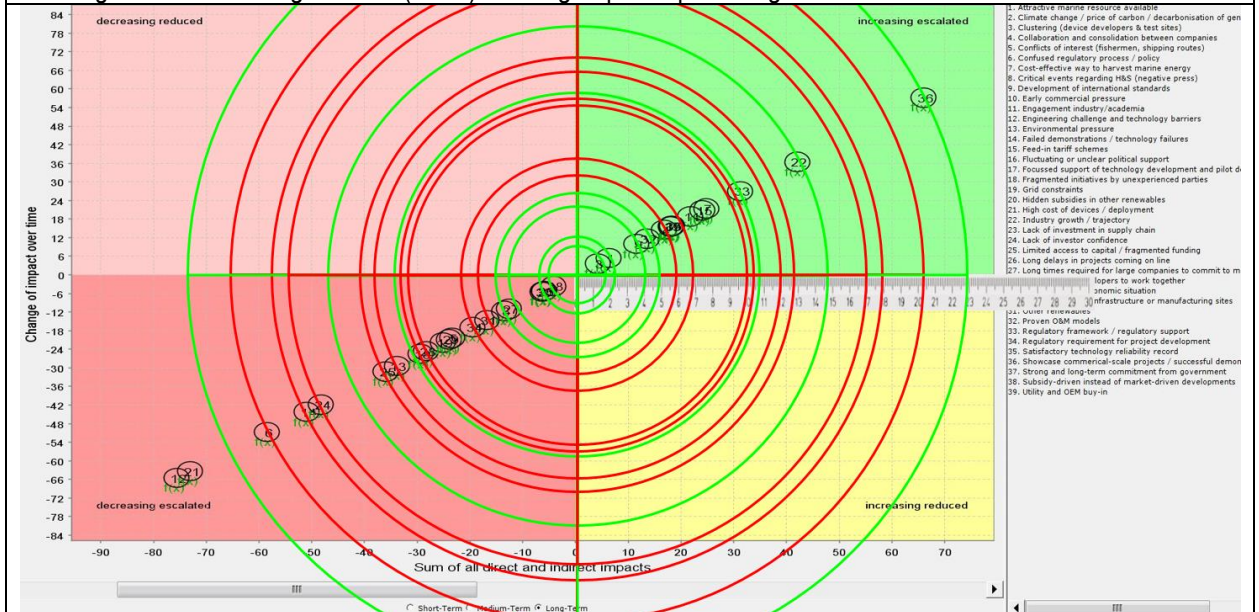


## 1.2 Insight Matrix Analysis

SD-model without time correlations: deletion of --- for short-term, -|- for medium-term and -||- for long-term:



Drawing section from insight matrix (detail) – both graphs coupled via generic term #36 with a value of 23:



**1.3 Comparison Table: Interview Data and results by SD-model without time impact**

Generic Term	Interview data [norm.]	SD-model 1: No time delays	Error [% points]
Strong and long-term commitment from government (#37)	100	100	0
Climate change / price of carbon / decarbonisation of generation capacity (#2)	47	47	0
Fluctuating or unclear political support (#16)	38	38	0
Engineering challenge and technology barriers (#12)	27	27	0
High cost of devices / deployment (#21)	27	26	1
Showcase commercial-scale projects / successful demonstrators (#36)	22	23	1
Confused regulatory process / policy (#6)	20	20	0
Failed demonstrations / technology failures (#14)	18	18	0
Lack of investor confidence (#24)	18	17	1
Industry growth / trajectory (#22)	16	15	1
Environmental pressure (#13)	13	12	1
Limited access to capital / fragmented funding (#25)	13	13	0
Fragmented initiatives by unexperienced parties (#18)	11	10	1
Low ability of developers to work together (#28)	11	10	1
Regulatory framework / regulatory support (#33)	11	11	0
Conflicts of interest (fishermen, shipping routes)	9		
Cost-effective way to harvest marine energy	9		
Engagement industry/academia	9		
Feed-in tariff schemes	9		
Grid constraints	9		
Negative global economic situation	9		
Collaboration and consolidation between companies	7		
Focussed support of technology development and pilot development	7		
Other renewables (#31)	7	6	1
Regulatory requirement for project development (#34)	7	7	0
Satisfactory technology reliability record	7		
Utility and OEM buy-in	7		
Critical events regarding H&S (negative press)	4		
Development of international standards (#9)	4	5	1
Long times required for large companies to commit to marine energy	4		
Proven O&M models (#32)	4	5	1
Attractive marine resource available (#1)	2	2	
Clustering (device developers & test sites) (#3)	2	2	
Early commercial pressure	2		
Hidden subsidies in other renewables	2		
Lack of investment in supply chain	2		
Long delays of projects coming on line	2		
No adequate port infrastructure or manufacturing sites	2		
Subsidy-driven instead of market-driven developments	2		

**E            System dynamics computer models**

**E.1          Model 1: Full-commercial power generation by marine energy**

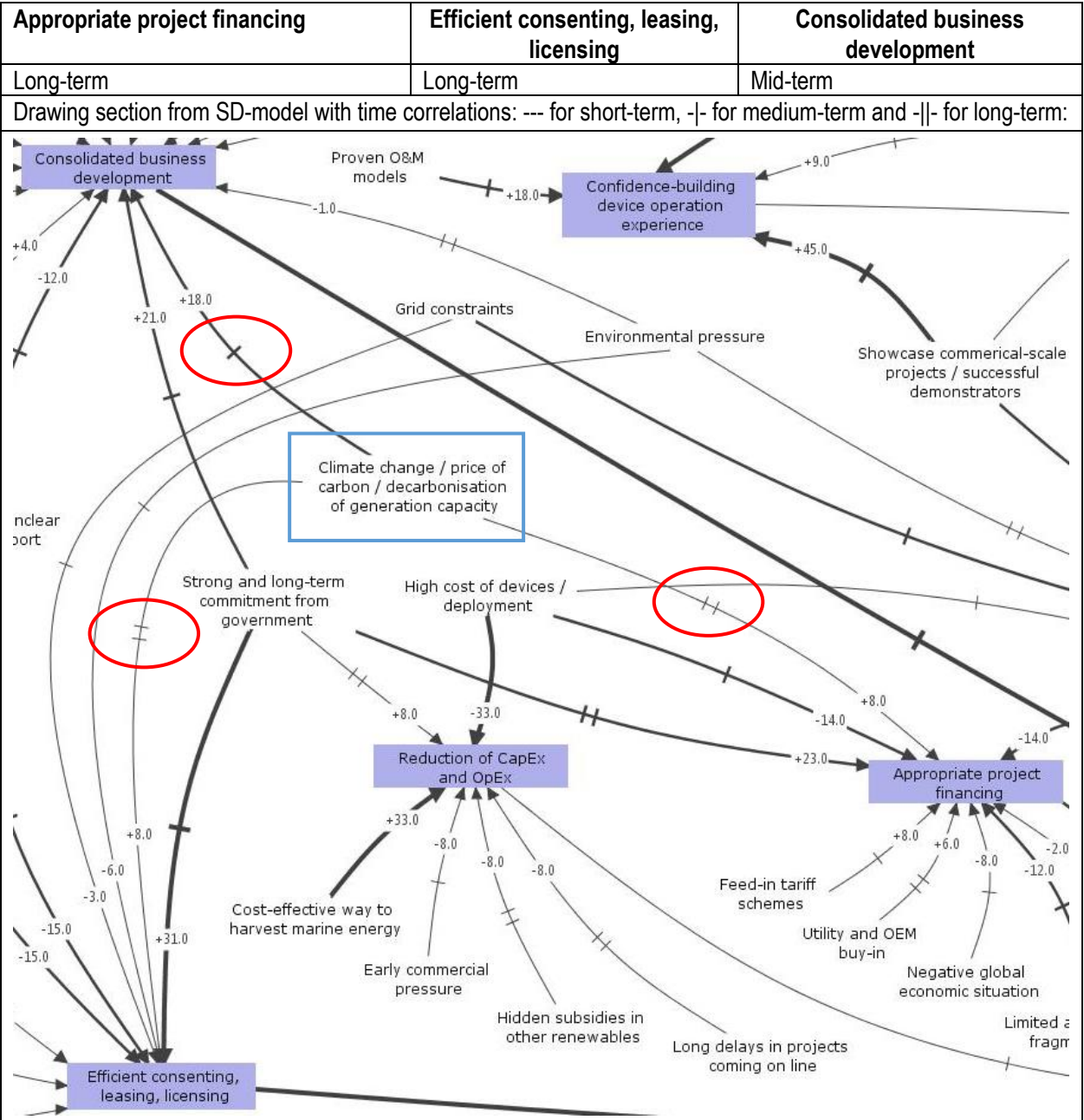
**E.1.4       Sensitivity and robustness**

**E.1.4.4     Impact by determination of time behaviour**

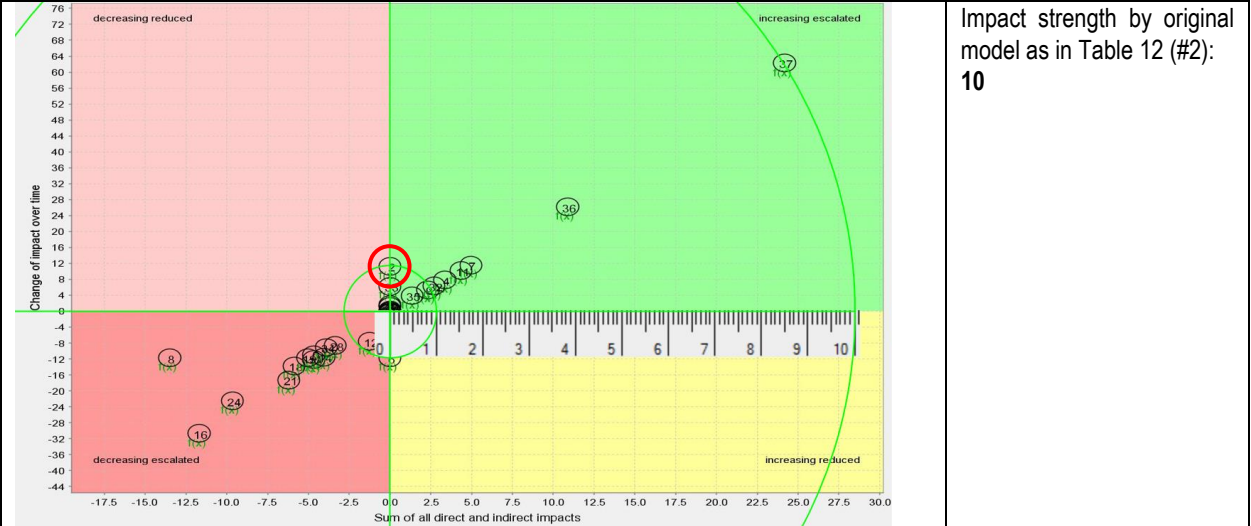
**E.1.4.4.2   Modification of time impact**

2 Generic term: Climate change / price of carbon / decarbonisation (#2)

2.1 Long-term / Long-term / Mid-term (original)



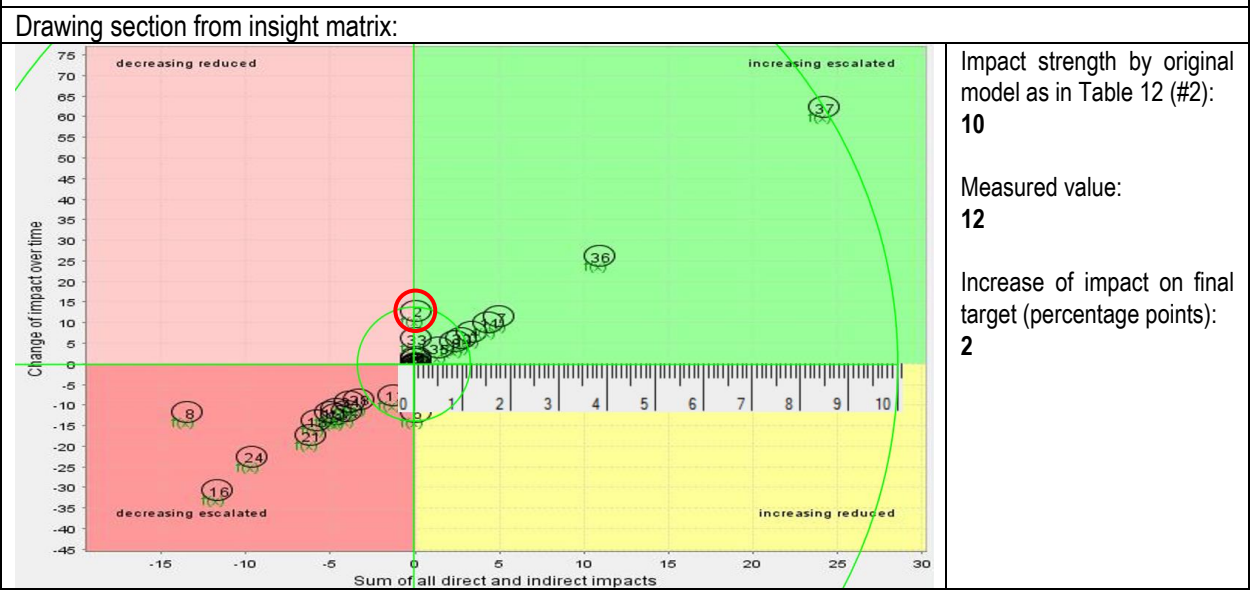
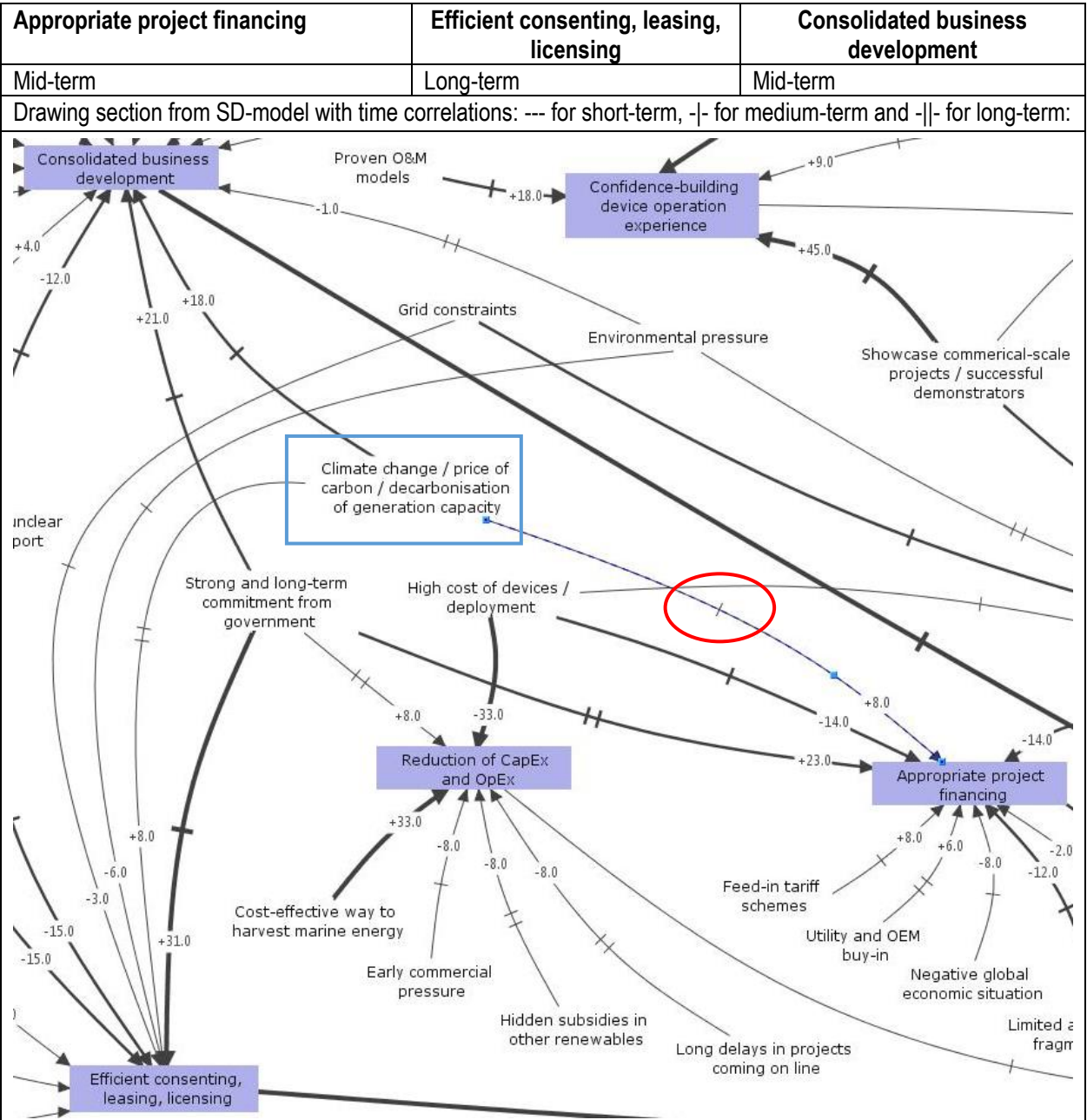
Drawing section from insight matrix:



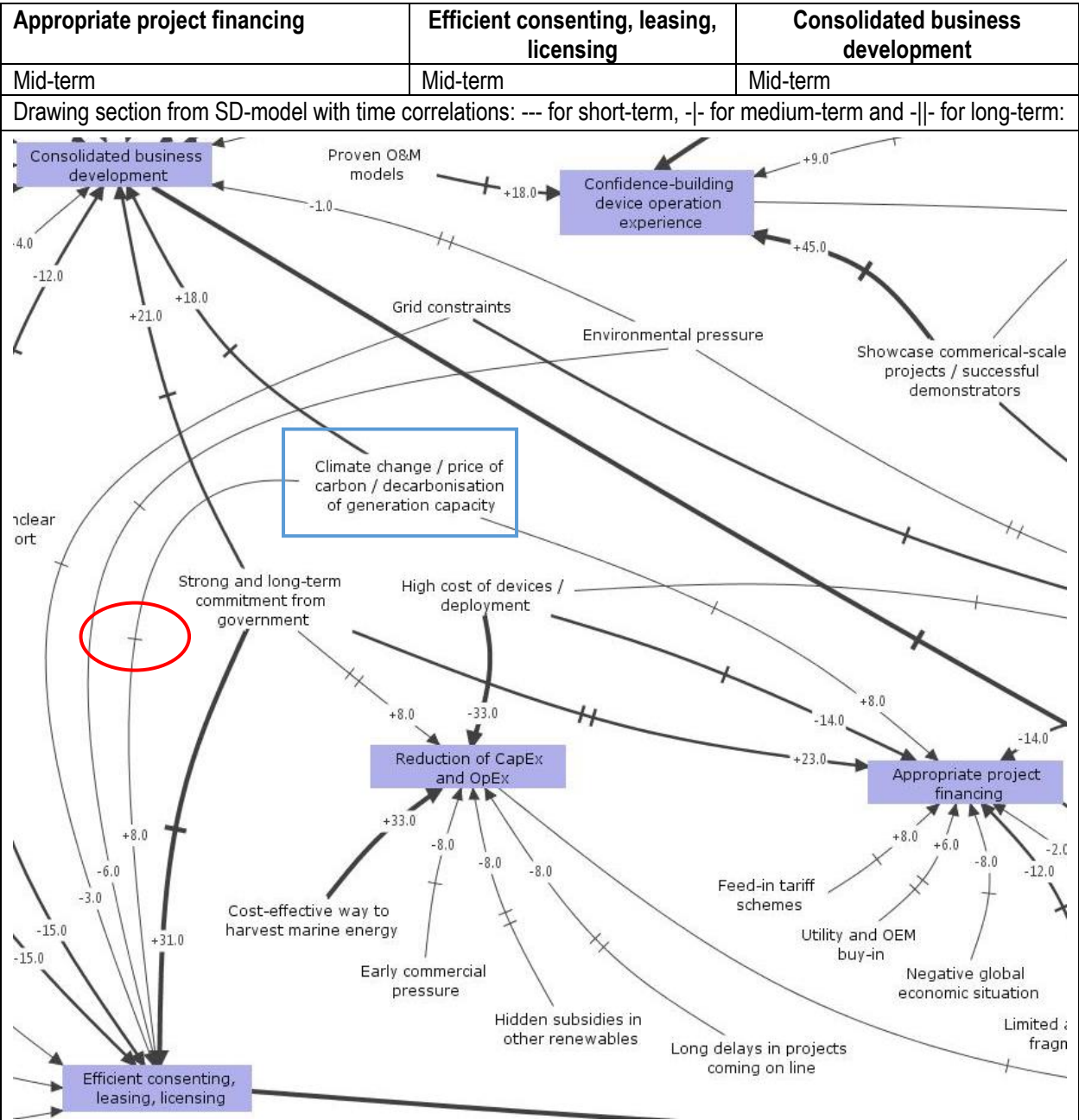
Impact strength by original model as in Table 12 (#2):  
10



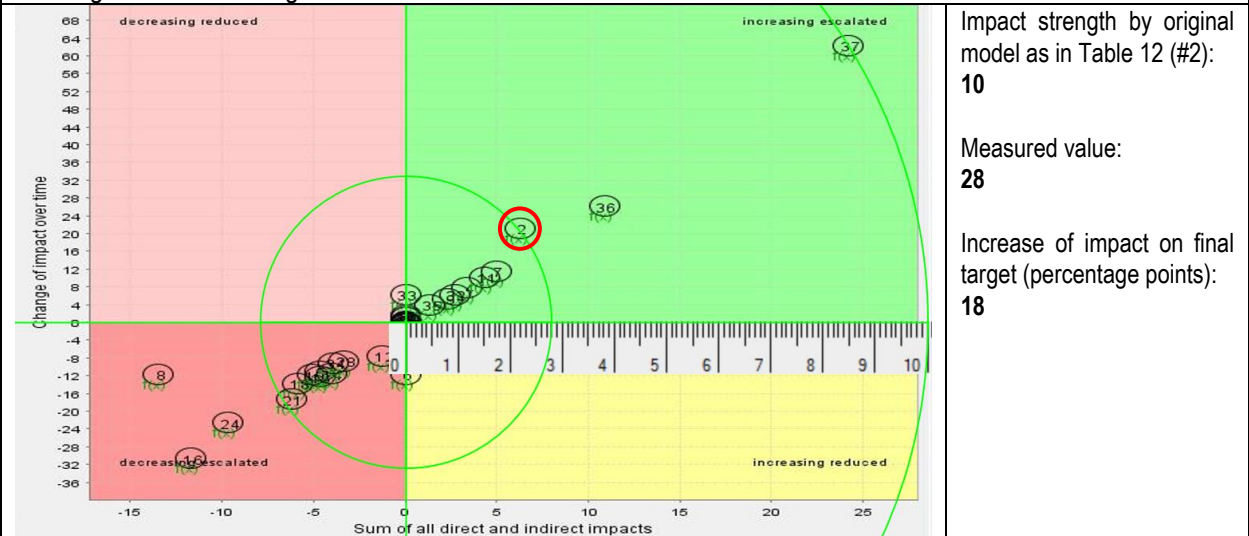
2.2 Mid-term / Long-term / Mid-term



2.3 Mid-term / Mid-term / Mid-term



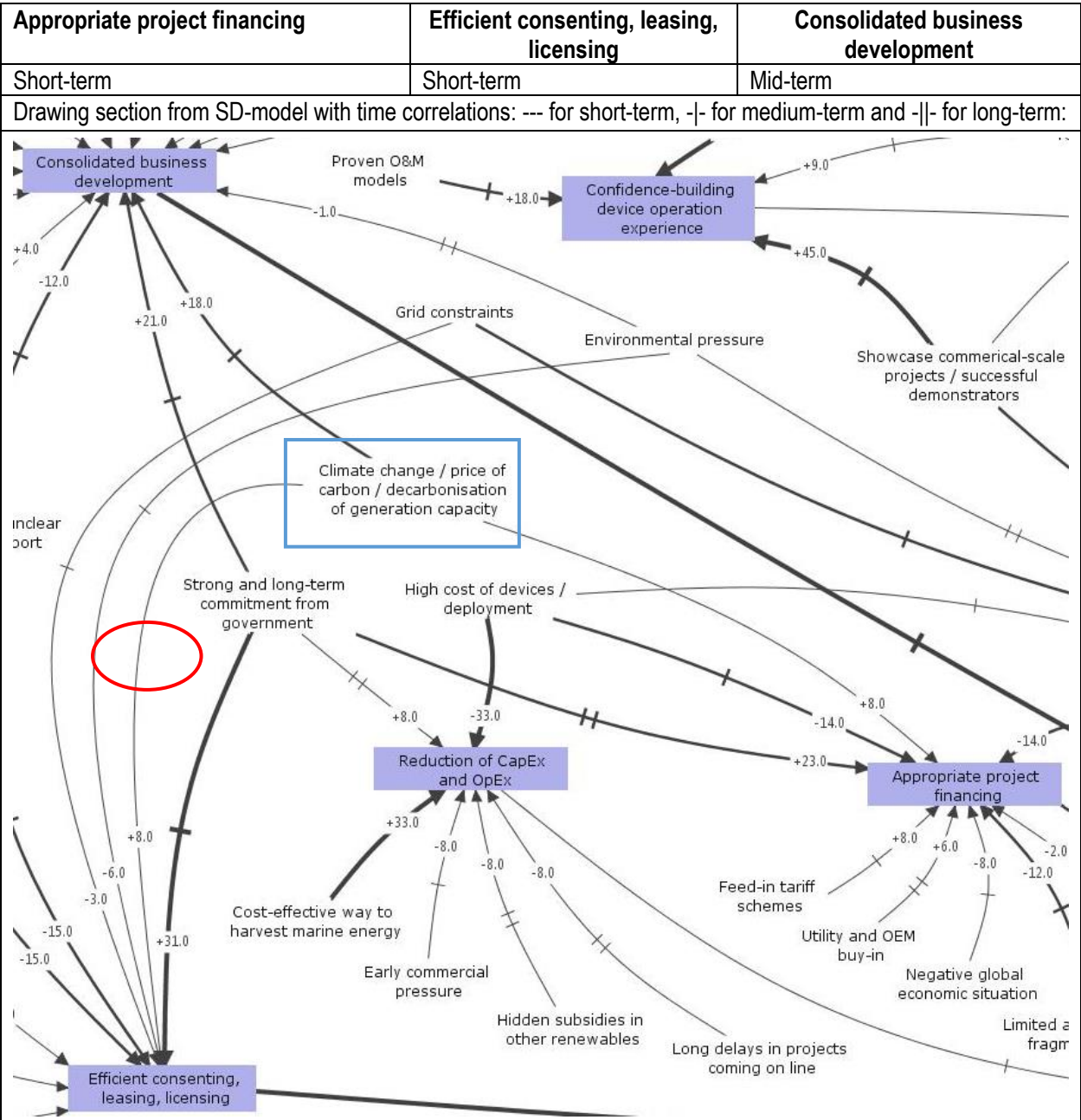
Drawing section from insight matrix:



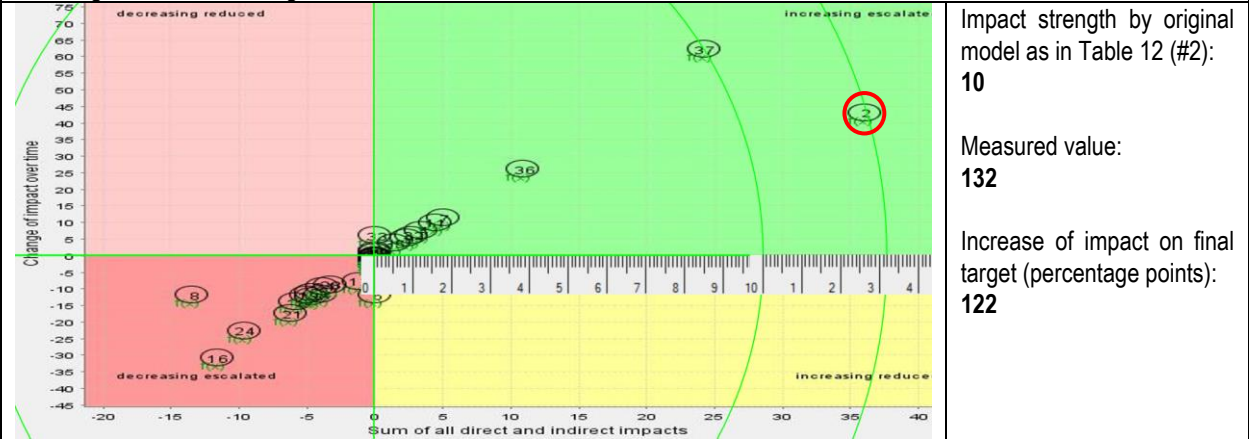




2.5 Short-term / Short-term / Mid-term



Drawing section from insight matrix:

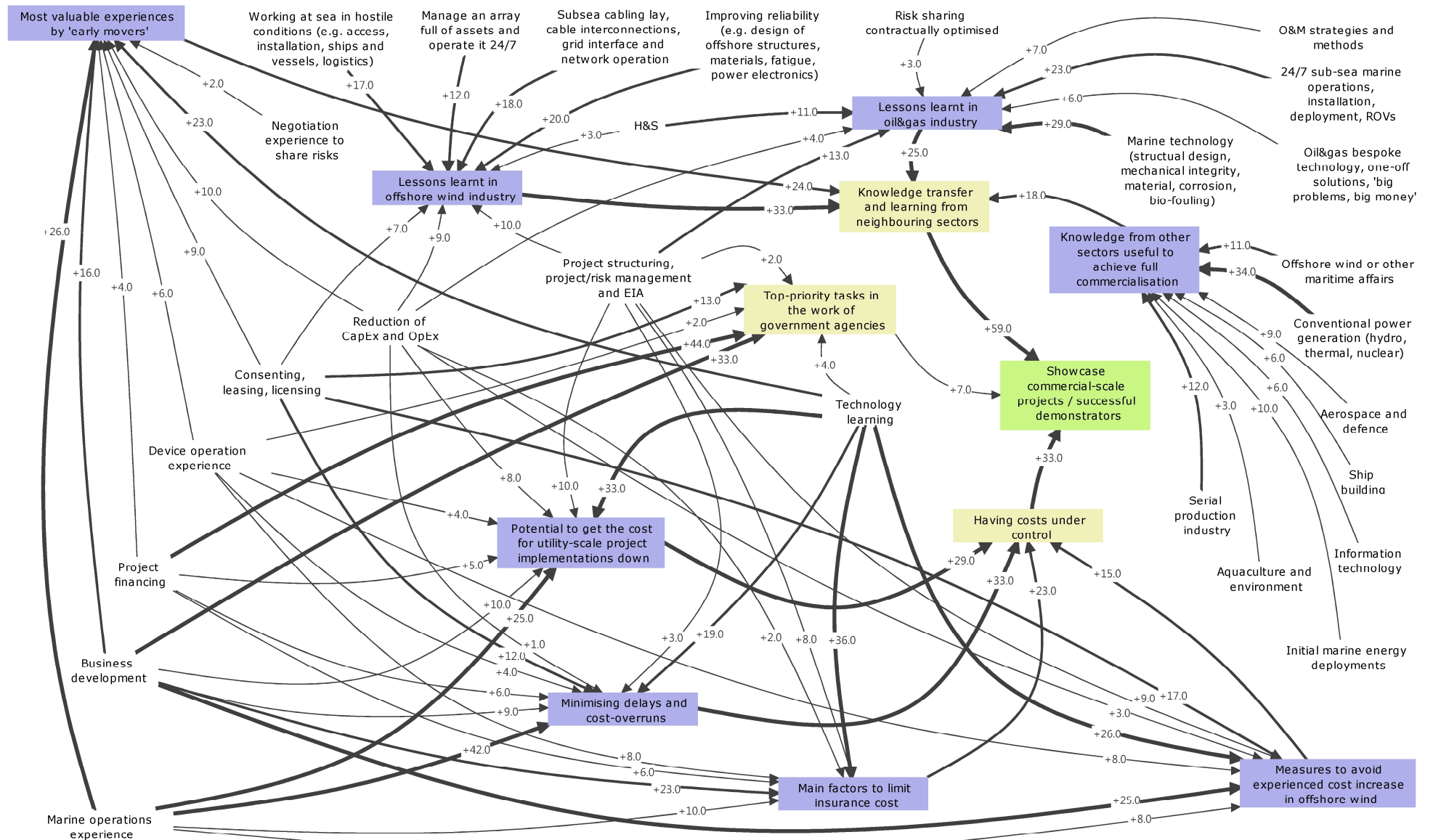






- E            System dynamics computer models**
- E.2        Model 2: Showcase commercial-scale projects / successful  
              demonstrators**
- E.2.1      Causal diagram**

**Model 2 (reinforcing): Showcase commercial-scale projects/successful demonstrators**



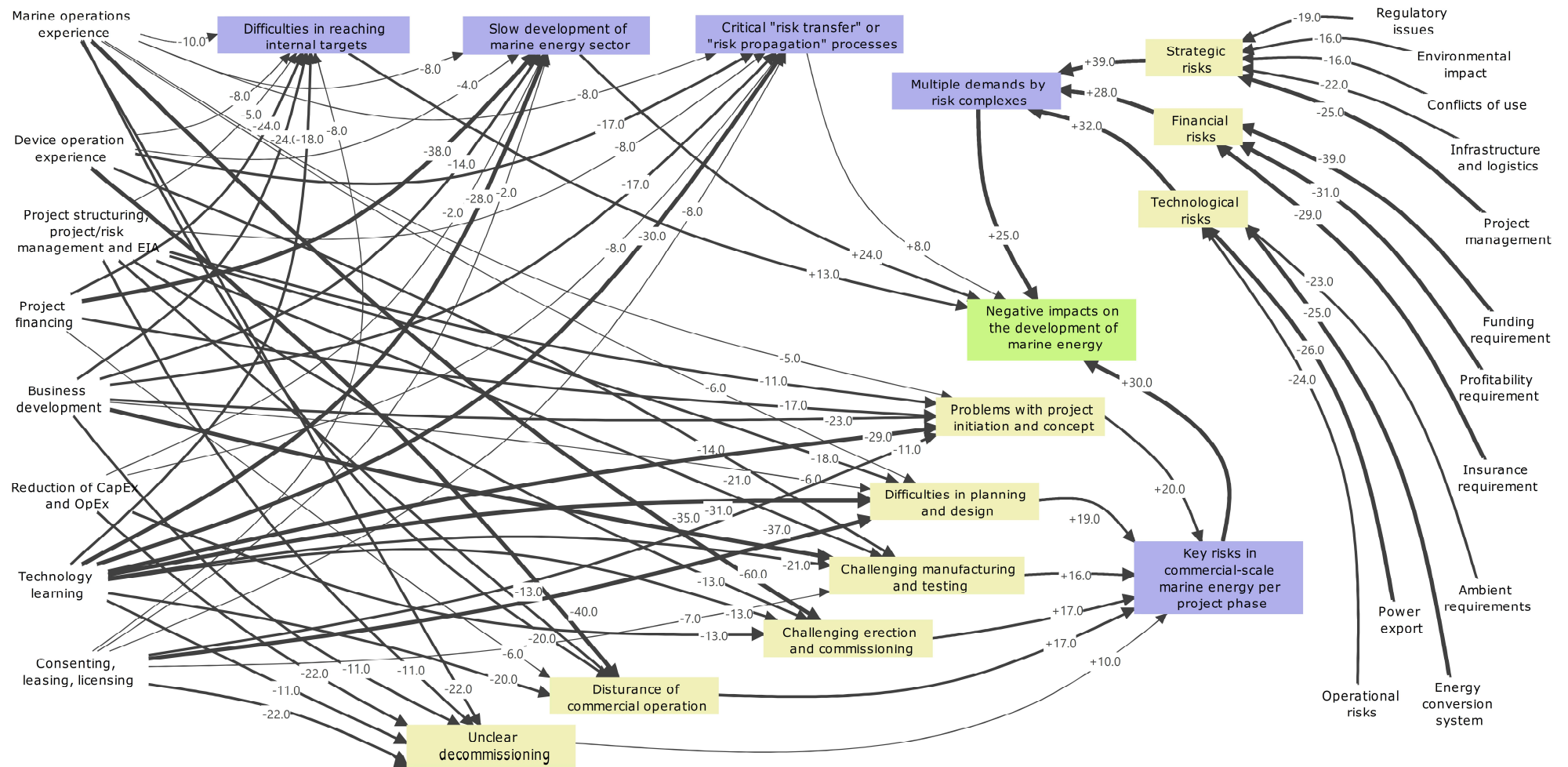
- E            System dynamics computer models**
- E.2        Model 2: Showcase commercial-scale projects / successful  
              demonstrators**
- E.2.2      Insight matrix**





- E            System dynamics computer models**
- E.3        Model 3: Negative impact on the development of marine energy**
- E.3.1      Causal diagram**

### Model 3 (countervailing): Negative impact on the development of marine energy

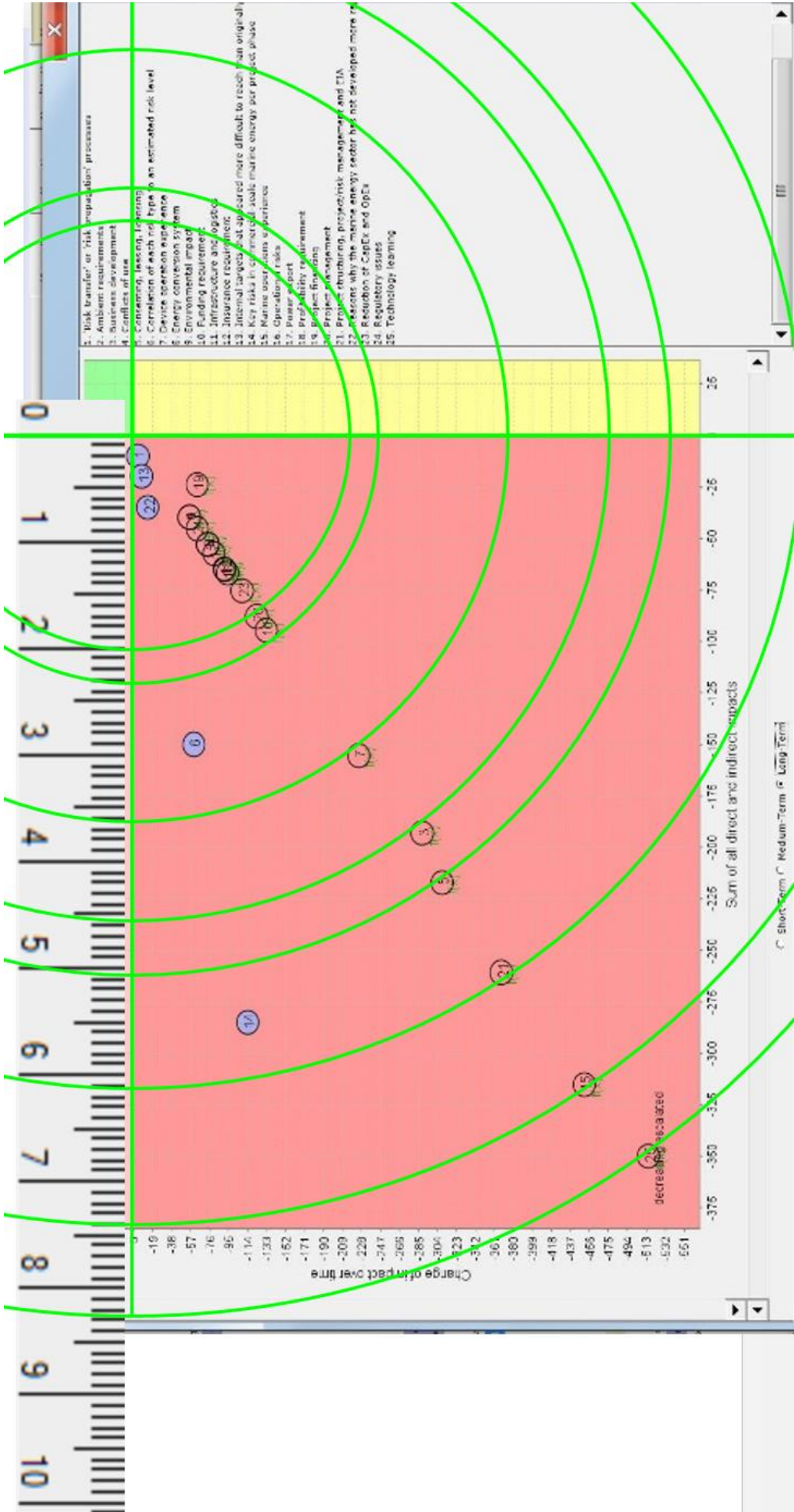


- E            System dynamics computer models**
- E.3        Model 3: Negative impact on the development of marine energy**
- E.3.2     Insight matrix**



Model 3 (countervailing): Negative impact on the development of marine energy

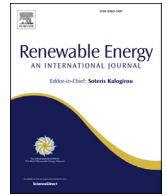
Overall / for calibration.



## **F Publications**

### **F.1 Scientific journal articles**

Bucher, R., Jeffrey, H., Bryden, I.G., Harrison, G.P. (2016) Creation of investor confidence: The top-level drivers for reaching maturity in marine energy, *Renewable Energy* 88, pp120–129, ISSN: 0960-1481, <http://dx.doi.org/10.1016/j.renene.2015.11.033> (originally presented at the 5<sup>th</sup> International Conference on Ocean Energy, 2014, Halifax, Canada)



# Creation of investor confidence: The top-level drivers for reaching maturity in marine energy



R. Bucher <sup>a,\*</sup>, H. Jeffrey <sup>a</sup>, I.G. Bryden <sup>b</sup>, G.P. Harrison <sup>a</sup>

<sup>a</sup> University of Edinburgh, Institute for Energy Systems, Mayfield Road, Edinburgh, EH9 3JL, UK

<sup>b</sup> University of the Highlands and Islands, Ness Walk, Inverness, IV3 5SQ, UK

## ARTICLE INFO

### Article history:

Received 27 October 2014

Received in revised form

30 October 2015

Accepted 8 November 2015

Available online 5 December 2015

### Keywords:

Marine energy commercialisation

Strategic drivers

Investor confidence

System dynamics

## ABSTRACT

Electricity generation by tidal current and wave power arrays represents a radical innovation and is confronted by significant technological and financial challenges. Currently, the marine energy sector finds itself in a decisive transition phase having developed full-scale technology demonstrators but still lacking proof of the concept in a commercial project environment. After the decades-long development process with larger than expected setbacks and delays, investors are discouraged because of high capital requirements and the uncertainty of future revenues. In order to de-risk the technology and to accelerate the commercialisation process, we identified stakeholder-wide balanced and realisable strategic targets. The objective is to name the top-level drivers for facilitating technology maturation and thus achieving market acceptance. Our analysis revealed that the two major risks for multi-megawatt projects (funding and device performance) are directly interlinked and that co-ordinated action is required to overcome this circular relationship. As funding is required for improving device performance (and vice-versa), showcasing an “array-scale success” was identified as the interim milestone on the way towards commercial generation. By this game-changing event, both mentioned risk complexes will be simultaneously mitigated. We observed that system dynamics modelling is appropriate for an unbiased analysis of complex multi-level expert interview data. The applied research model was found to be efficient and allows a regular re-assessment of the strategic alignment thus supporting the adaptation to a complex and continuously changing socio-technical environment.

© 2015 Elsevier Ltd. All rights reserved.

## 1. Introduction

Marine energy is arising in an era of global interest in low-carbon electricity generation and is confronted with a market environment in which other renewables are struggling to be cost competitive with non-renewable sources. Even though there are significant public support programmes, the commercialisation of marine energy represents a major technical and financial challenge. Since 2003, the European Commission has allocated up to €140 m towards marine energy development and industry investment of more than €700 m in the last 8–10 years has triggered significant progress [1].

To become recognised as a mature generation alternative, marine energy needs to prove a range of referenceable application cases in commercial project environments. Managing the market entry process represents an ambitious undertaking that requires the unbiased identification and stakeholder-wide application of harmonised strategic principles. To tackle this problem, comprehensive expert interviews and system dynamics techniques were used to identify the top-level drivers. Representative interview statements, correlating with the determined strategic drivers, are put into context.

It was identified that, drawing on expert interviews, the two top-ranked risks for multi-megawatt tidal current and wave power array projects are “achieving funding” and “device performance”. Both are interlinked and will be mitigated simultaneously when achieving the “array-scale success”. As investor confidence mainly depends on proof of continuous grid-connected operation, attainment will represent a major turning point for the global marine energy business and is expected to finally trigger new investment required for large-scale deployment.

\* Corresponding author.

E-mail addresses: [r.bucher@sms.ed.ac.uk](mailto:r.bucher@sms.ed.ac.uk) (R. Bucher), [henry.jeffrey@ed.ac.uk](mailto:henry.jeffrey@ed.ac.uk) (H. Jeffrey), [ian.bryden@uhi.ac.uk](mailto:ian.bryden@uhi.ac.uk) (I.G. Bryden), [gareth.harrison@ed.ac.uk](mailto:gareth.harrison@ed.ac.uk) (G.P. Harrison).

To efficiently pass the present “pre-profit” phase and to head towards commercial-scale projects, coordinated interaction within and between the stakeholder groups is required. A conclusive strategy to orientate the marine energy development process must integrate the dynamic and complex interplay between the different stakeholders.

The focus of the research is on de-risking the technological concept and thus attracting investment to finally establish marine energy as a competitive generation alternative with commercially viable projects implemented on a regular basis.

## 2. Literature review

### 2.1. Investors' attitudes towards wave and tidal

Leete et al. [2] report that investors engaged in marine energy venture capital funding were unlikely to make any future investments in early stage device development. They found that venture capital investors are not closed to the industry completely, but the current level of risk and uncertainty of future revenues are discouraging them from investing. It is underlined that a track record of continuous device operation of at least 6 months is a pre-requisite for further engagements. Investors profiled by Masini and Menichetti [3] showed a clear preference for more mature, proven technologies with only 3 of 93 investors analysed having any exposure to wave and tidal energy. Given the relatively small scale of today's marine energy developments, investors are able to achieve similar or greater returns on larger developments of more proven energy technologies. Magagna and Uihlein [4] describe that high costs associated with marine energy, combined with the unproven status of the technologies, hinder investors' confidence.

These studies clearly describe the present investment climate and investor attitudes based on experience. As improvement measures are rarely proposed, this paper intends to name effective strategies to overcome the present locked-in situation and to provide arguments for investors to direct their financial engagements. The required efforts for putting corresponding measures into practice can be justified by the long-term benefits after the market breakthrough.

### 2.2. Can marine energy compete on cost?

According to the UK Department of Energy & Climate Change [5], the projected levelised cost of electricity generation (LCOE<sup>1</sup>) for marine energy in the year 2020 will range between 20 and 42 c€/kWh. Spain expects LCOE for that period of time of 21–33 c€/kWh [6]. Previsic et al. [7] have similarly suggested commercial opening costs of electricity for wave power between 20 and 30 c€/kWh. LCOE for onshore wind in the UK are projected of 9–15 c€/kWh by 2020 and for offshore wind of 13–22 c€/kWh [5]. RenewableUK [8] believes that the current LCOE for leading tidal current devices is around 36 c€/kWh, compared with 48 c€/kWh for wave power devices. As onshore wind energy represents the reference for cost-competitive renewable power, it shall be noted that the global average LCOE dropped from 19 c€/kWh in 1992 to 6 c€/kWh in 2014 [9]. Offshore wind farms at very good locations currently achieve LCOE of 11–19 c€/kWh [10]. Presently, the kWh-costs in marine energy are far too high to compete with other renewable or even non-renewable generation options [11]. Taking into

consideration the projected LCOE in the UK for 2020, the cost for tidal current might touch the upper end of the offshore wind range. For the forthcoming years, governmental support programs will be indispensable to further drive research and development [12]. In offshore wind – with a global installed capacity of 5.4 GW [13] – it is expected that a further 15 years of subsidies will be required [14].

Although there is the perspective for continuously decreasing LCOE for marine energy, we see the need to concentrate on rapidly achieving a multi-company based market breakthrough. If the first commercial array projects do not deliver good returns for investors, the significant industry investment of the last years might not be compensated and the focus of interest would finally move to other technologies. It is evidently in the interest of all engaged stakeholders to make use of the available window of opportunity in order to overcome the current pre-profit phase and to establish a new and innovative industry.

### 2.3. Protected spaces for innovation

Carlsson et al. [15] identified in the course of innovation studies, that market-linked technological systems are not static but need to evolve continuously to be able to survive. Due to regular transformations in the embedding socio-technical system, which encompasses the co-evolution of technology and society, the lines of technology development need to be regularly re-adjusted [16]. Alkemade et al. [17] explain from an innovation studies perspective, that new technology often has difficulty in competing with embedded technologies and suggests that most inventions are relatively inefficient at the date when they are first recognised as constituting a new innovation. Negro et al. [18] hereto formulated more specifically, that renewable energy technologies find it hard to breakthrough in an energy market dominated by fossil fuel technologies that reap the benefits from economies of scale, long periods of technological learning and socio-institutional embedding. If the gap between new and established technology is very large and if there is a “paucity of nursing” or missing “bridging segments” that allow for a gradual generation of increasing returns, a new technology may never have the chance to rectify the initial disadvantages [19]. Scholars in evolutionary economics have highlighted the importance of “niches” that act as “incubation rooms” for radical novelties, shielding them from mainstream market selection. Such protected environments are enabled to overcome conventional organisational (i.e. socio-technical) inertia (e.g. Refs. [20,21]). Bergek et al. [22] confirm that technology development can best take place within specially created learning spaces that allow a new technology to develop a technical trajectory (for reaching maturity or even a dominant design). Erickson and Maitland suggest that “nursing markets” need to be created to support the technology breakthroughs, taking advantage of windows of opportunity that drive adjustments in the socio-technical regime [23,24].

For a decade, we have seen that significant development in the marine energy sector is taking place within such “protected incubation rooms” in the form of marine energy test facilities or subsidised pilot projects. Research, however, recognises an underlying time pressure, as artificially created learning environments can be maintained only for a limited time.

## 3. Objective of the research

The referenced primary literature describes the difficulties which the marine energy sector faces and makes investors' restraint evident. Although ideas for improving the investment climate are outlined, the presentation of a conclusive set of measures that can be implemented by the stakeholders in order to

<sup>1</sup> LCOE is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.



advance the commercialisation of marine energy was not found. The current literature lacks well-founded arguments and coordinated strategies to work stepwise towards market acceptance. This contribution is intended to close the gap in literature by qualifying the mid-term goals and by providing a coherent strategy to overcome the pre-profit phase. The focus is on presenting methods to de-risk the technology and to govern the market entry process in order to create investor confidence. The identification of a directed and concise strategy for the market launch in one single attempt is crucial. If stakeholders realise their individual benefit by the subsequently presented measures, their willingness to implement them will increase.

## 4. Materials and methods

### 4.1. Research design

The research includes a combination of qualitative and quantitative methods, which divide the study into three phases. In phase one, a target-oriented questionnaire was presented, which formed the basis of expert interviews to obtain a broad-perspective image of the current situation and plans. In phase two, the interview data were systematically processed and formed the input for the configuration of representative system dynamics computer models. In phase three, milestone events on the way towards commercialisation were determined and corresponding strategic principles to achieve them identified.

A basic principle applied in this research is to create new insight by compiling different sources of knowledge for the elaboration of an optimum strategy towards achieving market competitive generation. Okhuysen and Eisenhardt [25] describe in a study in the field of experimental behavioural science, that new knowledge is generally created by applying multiple perspectives to the same information. Huang and Newell [26] underline in their research on cross-functional projects with multiple stakeholder groups, that it is vital to understand the dynamics of organisational learning and strategic change initiatives.

In order to follow the principle of multiple perspectives, experts from all stakeholder groups were invited to contribute with their individual experience and know-how. Based on this multi-disciplinary attempt, an all-encompassing appraisal became possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests only. Special attention was dedicated to include a wide spectrum of stakeholders and the performance of data compression in a transparent and fact-based manner.

To master the amount and complexity of the cross-category information and to systematically identify the fundamental drivers, all data were uniformly consolidated to form the basis for the configuration of detailed cause–effect relationship diagrams. The final system dynamics models emerged from “iterative cycles of data gathering, feedback analysis, implementation of measures and result evaluation” as described by Formentini and Romano [27] in a knowledge management context.

The use of system dynamics modelling techniques assures an open-integrative, instead of detailed-specialist, character of the research. Based on this multi-disciplinary approach, an all-encompassing appraisal becomes possible by avoiding concentration in a limiting manner on stakeholder-specific views or interests. The methodology applied enables a dynamic interplay between knowledge creation, knowledge compression and targeted knowledge diffusion.

### 4.2. Hypothesis

Regular commercial marine energy projects will be realised under institutional financing and according to international procurement principles. To ensure investor engagement, the reliability of the technological concept has to be proven in advance.

The research is oriented around the hypothesis:

*The unbiased processing of expert interview data by system dynamics computer modelling allows the identification of stakeholder-wide applicable strategies that create investor confidence and thus facilitate the marine energy market breakthrough.*

The long-term focus is on establishing marine energy as a market competitive generation alternative with commercially viable projects implemented on a regular basis.

### 4.3. Questionnaire

For the survey, a questionnaire with a total of 90 questions was prepared, out of which 48 were yes/no questions and 42 were qualitative, referring to stakeholder-related experience. With the aim of harmonising and uniformly directing the research, the interviewed experts, in a first set of questions, provided estimations of the characteristics of future tidal current or wave power projects (capacity ~40 MW, implementation ~2025, investment ~120 m€). The next set of questions was directed towards knowledge transfer by asking “Which are the most valuable experiences gained by the early movers in the marine energy sector?” and “Which lessons learnt in the offshore wind and oil & gas sectors can be transferred to marine energy?”. In a further section, focus was put on achievements and planning by asking “What do you consider as main reasons why the marine energy sector has not developed more rapidly?” or “Which should be top-priority tasks in the work of the other stakeholder groups to reach full commercialisation?”.

Cost aspects were examined by asking “Where do you see the greatest concerns for delays and cost-overruns in marine energy projects?” or “Where do you see significant potential to get the cost for utility-scale project implementations down?”. The question defining the basic system dynamics model was of qualitative nature by focussing on positive and negative impact factors for reaching “full-commercial marine energy”.

Finally, a quantitative assessment of the risk levels in commercial-scale marine energy per project phase was carried out by rating a total of 40 risk types out of four risk categories (strategic, financial, technological, operational).

### 4.4. Expert interviews

By contacting 136 representatives from 15 stakeholder groups, 71 feedbacks were received, leading to 11 personal and 15 telephone interviews, as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were significantly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups (see Table 1) was retained for the analysis, corresponding to an effective return rate of 32.4%, which is higher than usual for studies of this nature [3]. A total number of 2129 individual replies were grouped to formulate higher-level correlations as basis for the computer-based system dynamics modelling. All semi-structured single person interviews were conducted either face-to-face at the premises of the interviewee or by telephone between June 2012 and April 2013. No follow-up interviews were carried out.

**Table 1**

List of participating stakeholders.

---

Government (associations) & trade organisation: The Scottish Government, Marine Scotland, Energy Technologies Institute, Carbon Trust, Department of Energy and Climate Change, The Crown Estate, Scottish Natural Heritage, Centre for Environment, Fisheries & Aquaculture Science, RenewableUK, Technology Strategy Board.
Certifying authorities: Det Norske Veritas, Lloyd's Register.
Investors & lenders: Green Giraffe.
Law firm: Eversheds International.
Academia & research: University of Washington, University of Edinburgh, National Taiwan Ocean University, Irish Marine Institute.
Engineering consultancies: Natural Power, Xodus Group, Tecnalia Research & Innovation, South West Renewable Energy Agency, Royal Haskoning.
Project developers: Emera, EDF, Electricity Supply Board, Iberdrola.
Owners & operators: ScottishPower Renewables, Ente Vasco de la Energía.
Transmission system operator: Scottish and Southern Energy Renewables.
Device manufacturers: Marine Current Turbines, Pelamis Wave Power, Wavebob, Siemens, Wave Star, Ocean Renewable Power Company.
Offshore contractors: 6 contacted (no feedback).
Test site operators: European Marine Energy Centre, Fundy Ocean Research Centre for Energy, National Renewable Energy Centre, Minas Basin Pulp & Power, France Energies Marines.
NGO: Greenpeace.
Offshore wind industry: Dong Energy Power.
Oil & gas industry: 4 contacted (no feedback).

---

#### 4.5. System dynamics computer modelling

The information gained by the expert interviews was compressed by the use of ordering terms based on which a total of three system dynamics<sup>2</sup> computer models were configured. For the basic model, all positive (reinforcing) and negative (countervailing) influences on the pre-defined target of “full commercial power generation by marine energy” were grouped and inter-correlated (Fig. 1).

The model was built one-on-one to the interview replies, so that it directly reflects the experience and expectation of all interviewed stakeholders. Out of a total of 234 individual replies, 16 top-level driving factors, essential for achieving commercial power generation, were identified and concentrated into three milestone terms:

- (i) Government support: The long-term commitment from government represents the basis for progress of the sector. Early stage developments depend on coordinated funding mechanisms and fiscal measures as well as an efficient consenting process.
- (ii) Array-scale success: The 2nd ranked top-level driving factor (showcase commercial-scale projects/successful demonstrators) forms the essential element of this interim milestone that triggers further development.
- (iii) Cost reduction: After having successfully demonstrated the array-scale success, the cost of energy will decline due to serial manufacturing and technology convergence.

As the singular characteristics of government support are outside the range of this paper, the context around achieving the second milestone term “array-scale success” is examined in detail by identifying the respective reinforcing and countervailing impact factors. Based on the findings suggesting the prioritised focus on showcasing commercial-scale projects, a second (see Fig. 2) system dynamics model was developed.

This new target was examined in detail by analysing 671 correlated interview replies. After calculating the ranking of impact factors and the determination of top-level driving factors, representative core statements from the interviews were allocated. Subsequently, strategies for de-risking the technology and governing the market entry process were elaborated.

To make full use of the insight gained in the course of the interviewing process, the negative impact factors (generated from 1712 replies) hindering, delaying or countervailing the development of marine energy were examined in a third system dynamics model [28]. The target factor was set as “negative impact on the development of marine energy”. Consequently, the central cluster of impact factors acting on the interim milestone “array-scale success” was tested by processing the negative impacts. By taking this diametrically opposite perspective, the research findings were further substantiated and balanced.

In Table 2, the most relevant recommendations and support options identified for sector-specific orientation are given. They are based on the prioritisation calculated by the system dynamics software (for models 2 and 3) and the compression of corresponding interview statements.

The system dynamics computer models were designed and configured exclusively based on the empirical data obtained through expert interviews. The result ranking calculated by the simulation software represents superordinate knowledge and correlates to information usually available to management.

## 5. Results

### 5.1. The game-changing “array-scale success”

Reliability is an important factor of success for all emerging technologies. In marine energy, the reliability proof remains a major challenge, as most devices to date have been in the water only for short periods of less than one year. In the course of the expert interviews, the importance of focussing on “array-scale activities” and the need to “to get pilot farms built” was repeatedly stressed. Most answers to the question “In which areas is research most required to accelerate the development of marine energy?” referred directly to multi-device arrangements such as “array-scale design”, “hydro-dynamic modelling of arrays”, “array-scale maintenance”, “the need for design tools to facilitate cost-effective array-scale development” and “to see first arrays progress through FID<sup>3</sup>”.

The prevailing top-ranked risks (“achieving funding” and “device performance”) are directly interdependent as investor confidence depends on track records of continuous device operation – and vice versa. In the centre of this area of conflict we find the “array-scale success” because passing this milestone will give

<sup>2</sup> As an initial step in approaching the characteristics of complex systems, in the mid-1950s, J.W. Forrester developed system dynamics as “a methodology and mathematical modelling technique for framing, understanding, and discussing complex issues and problems”.

<sup>3</sup> Final Investment Decision (see “FID enabling for renewables” by The Department of Energy & Climate Change, UK).

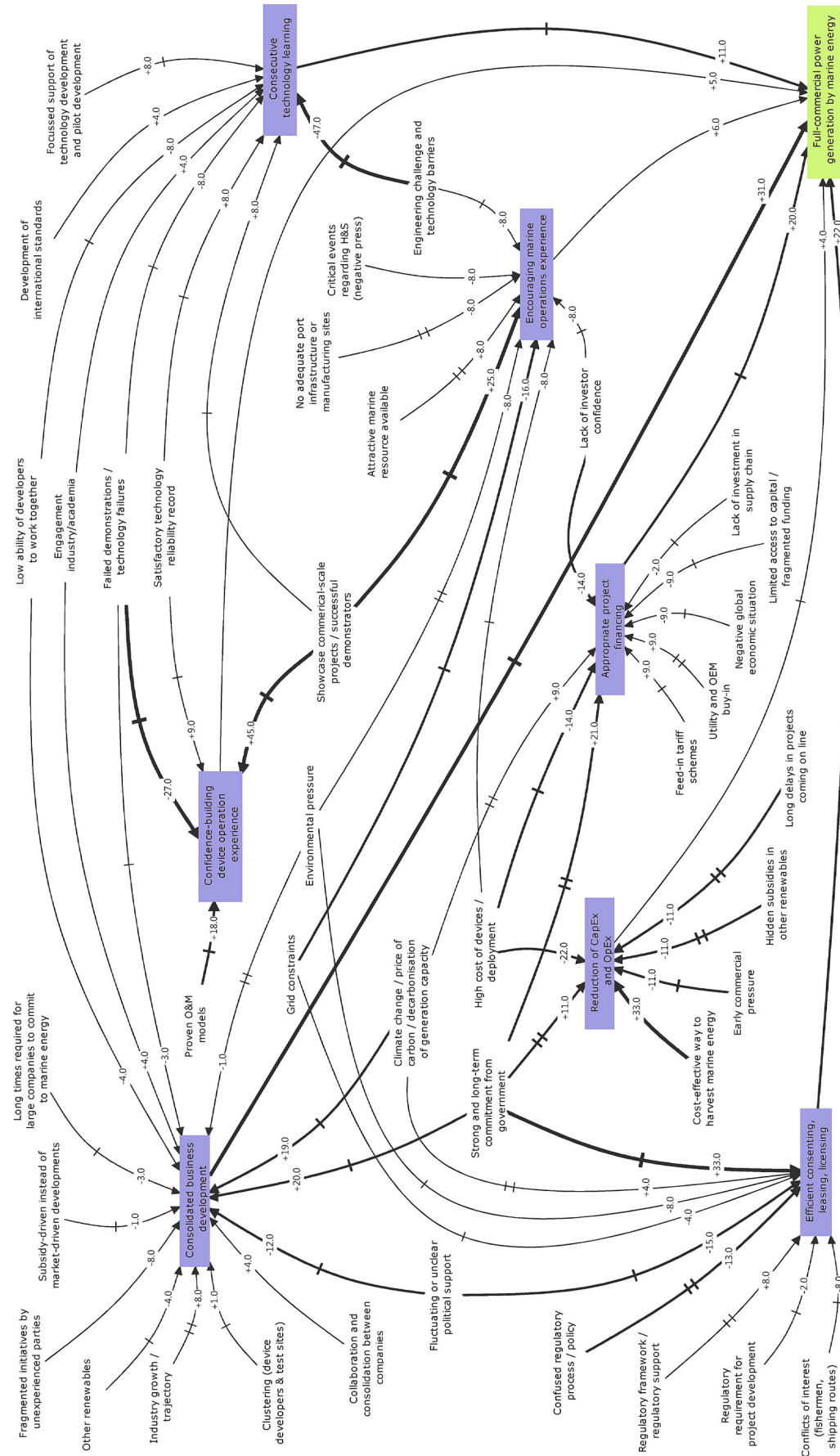


Fig. 1. System dynamics model: "Full-commercial power generation by marine energy".

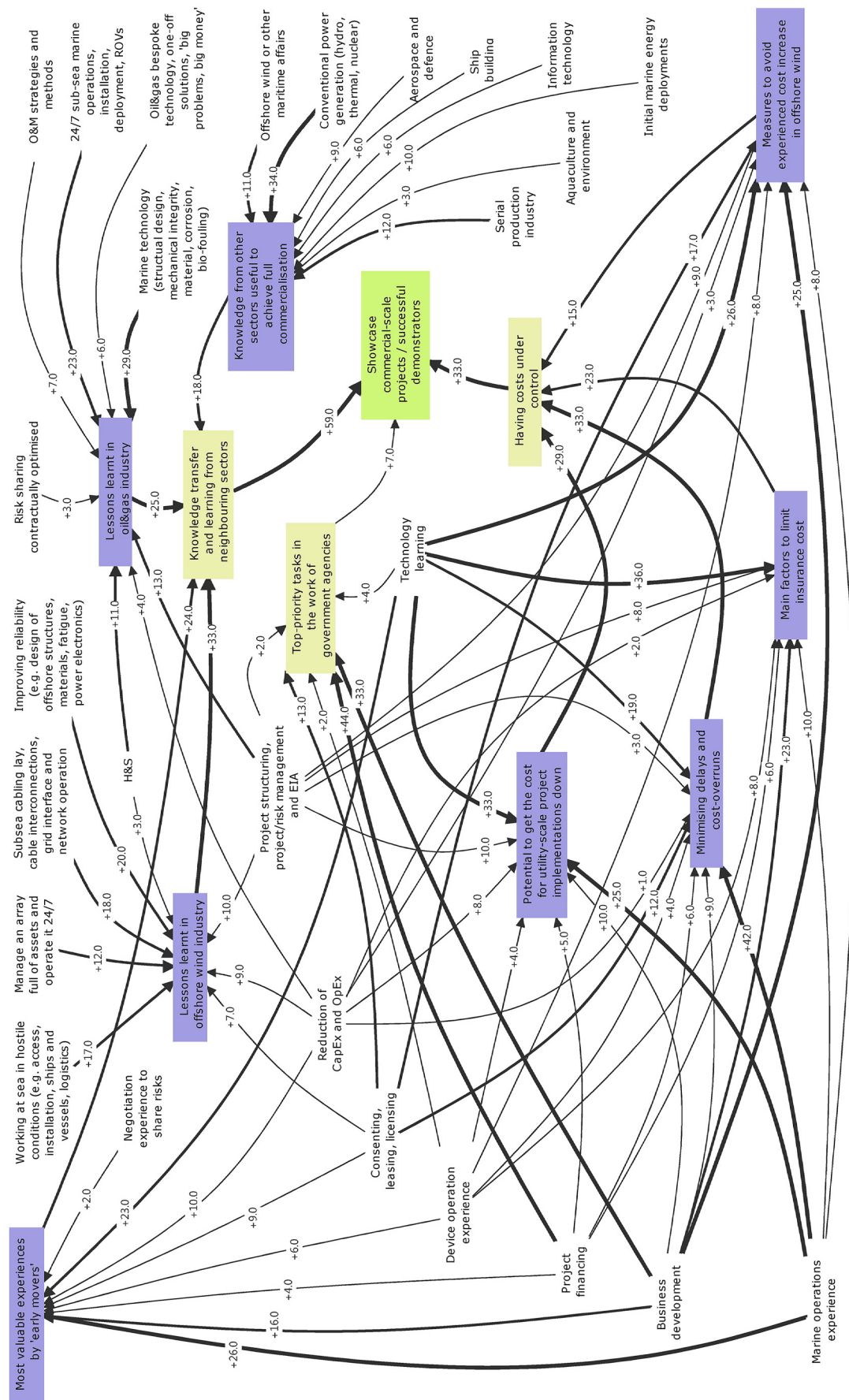


Fig. 2. System dynamics model: "Showcase commercial-scale projects".



**Table 2**  
Strategic orientation for the marine energy stakeholder groups.

<b>Technology</b>
Adopt systems engineering principles inspired by the space-/aircraft industry
Consider that extreme engineering is required with a focus on survivability and reliability
Reduce the number of technological concepts (technology convergence)
Develop multi-applicable technologies (standardisation of components) and joint concepts
Design for installation and maintenance purposes
Minimise the lack of collaboration and improve knowledge sharing
Gain offshore deployment experience with full-scale devices
Move from device testing towards array-scale activities under open sea conditions
Integrate risk management into project management
Consider the need to restructure and commit to the supply chain
<b>Policy</b>
Facilitate consenting, leasing, licencing (i.e. with a single point of handling the process)
Promote cross-interaction between renewables
Stimulate appropriate risk sharing between the stakeholders
Encourage initiatives to bring in expertise from offshore oil & gas marine operations
Focus on availability of qualified personnel and heavy marine services
Underline the importance of knowledge sharing (central bottleneck)
Improve collaboration and alignment between industry, utilities, academia and developers
Support grid-connected test facilities and pilot zones
Support strategies for grid operation with significant wave and tidal power in-feed
Simplify access to the international (out of Europe) market
<b>Financing</b>
Recognise that pilot projects with availability records provide confidence in core technology
Support technologies with declared synergies towards off-shore wind
Consider the likelihood of early-stage failures and the failing in unexpected parts of project
Keep in mind that realism is required when it comes to the (global) scale of the industry
Focus on cost of energy and not on capital expenditure
Consider that the cost of energy production is dependent on the capacity deployed
Evaluate the insurability of projects
Recognise differences to offshore oil & gas with regard to design, manufacturing, logistics
Realise the advantage of working with the already existing companies in the market
Encourage contract structuring and contract standardisation as in onshore wind

confidence in the industrial sector and de-risk investments in commercial projects. As the preparation and management of array-scale success is of central relevance for the continuous development of the marine energy, effort was put in identifying the top-level strategic principles of technical-organisational nature for being considered to be implemented by the key stakeholders.

## 5.2. Strategic drivers for reaching maturity and creating investor confidence

### 5.2.1. Systems engineering

The interview participants identified reliability concerns as the top-ranked non-commercial risk. On the opposite side, poor reliability was mentioned as the key operational risk. The widespread perception of high cost and unproven reliability was mentioned as negatively influencing the sector. Representatives from a UK financial firm and a Canadian project developer emphasised that concerns regarding delays and cost-overruns mainly relate to reliability and durability as well as the performance of marine energy converters. A US academic named the need for longer baselines for system reliability and an R&D vice-chair outlined that reliability is more important than efficiency. According to a Scottish government employee, the failure of devices was the most fundamental and greatest single reason for projects being delayed or costs increased. Reasons why the marine energy sector has not developed more rapidly were repeatedly identified as due to the uncertainty of device performance. The need to demonstrate equipment reliability at utility-scale was mentioned by a machinery expert of a global maritime classification society. When asking for significant potential to get the cost for utility-scale project implementation down, the emphasis from a wave energy converter firm representative was on the orientation of development and research strategies at the US space-/aircraft industry and here

especially on the systems engineering principle. To achieve a satisfactory technology reliability record, experts recommend more focus on reliability in system design and the introduction of reliability modelling. In the course of the design and deployment of marine energy converters, regular system functionality checks, focussing on the final operation in open sea, grid-connected, multi-device arrays, are recommended. Senior members of classification societies stressed the uncertainty about reliability as a main risk factor and emphasised the need to focus on it.

### 5.2.2. Standardisation

When being asked about the most valuable experience gained by the “early movers”, a project developer’s head of offshore had “experienced negative impact by missing standardisation”. Considering the urgent need for consensus over standardisation, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). Another interviewee summed up the situation by saying “no standards, no results”. According to the opinion of a utility’s marine energy project manager, one of the top-priority tasks in the work of academia and research should be to concentrate on multi-applicable technologies, standardised devices and system components. A utility’s representative underlined the expectation to reduce the cost for commercial-scale project implementations by the positive impact of technology convergence.

### 5.2.3. Knowledge sharing

The limited sharing of knowledge in the industry and between project developers is seen by the strategy manager of a public-private partnership and the head of energy of UK’s innovation agency as one main reason why the marine energy sector has not developed more rapidly. A senior policy officer emphasised the need to transfer lessons learnt in the offshore wind industry in

order to avoid duplication of time and effort. The project manager for the implementation of the world's first commercial breakwater wave power plant underlined the need to improve the sharing of bad experience and testing data. To support progress, he suggested conferences be used to explain why things went wrong and to display the finally implemented solution.

#### 5.2.4. Maximising collaboration and minimising competition

In line with the findings on the limited sharing of knowledge, a lack of collaboration was reported. The artificial competition with on-/offshore wind was criticised by an Irish marine energy development manager as negatively influencing an uninterrupted progress. The interviewed head of development of a wave converter manufacturer underlined the attractiveness of exploring the prospects by co-locating wave and wind power devices.

#### 5.2.5. Offshore deployment experience

As the programme director of a leading centre of sustainable energy expertise outlined, with the aim of demonstrating the viability of electricity generation by marine energy, it is necessary to provide transparency to investors and to focus on “bringing some 10 MWs in the water”. The importance of design for installation and maintenance purposes was emphasised by the representative of a wave energy device manufacturer. As an example of lessons learnt in the offshore oil & gas industry being transferred to marine energy, a senior manager at a Canadian utility mentioned their focus on reliability and survivability.

#### 5.2.6. Risk management and risk sharing

The development manager of a wave energy converter firm explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He stressed the requirement to share risks by collaboration and to integrate risk management into project management. A law firm's contract expert highlighted that risk sharing should be contractually optimised to identify the most appropriate risk owners. Apart from the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms), he recommended contract splitting as practised in offshore wind. An owner's representative mentioned that engineering consultancies should share risk with project developers.

### 5.3. Result summary

Considering a business environment in which other renewable energy technologies operate in price-competition with conventional sources, the market entry of marine energy is seen as a one-off chance. Consequently, it is in the elementary interest of the manufacturing firms and related stakeholders to make best use of the pre-commercial period through an extraordinary level of sharing knowledge with competitors and by enforcing cooperative interaction. As noted by Jay and Jeffrey [29], support and transfer of generic knowledge is currently limited by early-stage commercial competition.

Major power projects are usually realised by institutional financing and under the terms of international competitive bidding. Consequently, in marine energy, a number of equally competent manufacturing firms will be required at the time of the wholesale market-rollout to ensure realistic pricing and to avoid single bidder dependency.

## 6. Discussion

### 6.1. Overcoming the pre-profit phase

Array-scale success represents the key interim milestone and has to be seen within the larger picture, characteristic for the power industry. For a marine energy technology breakthrough, positive and transparent feedback from a variety of longer term grid-connected and commercially operated multi-megawatt arrays is required. After concept maturity has been demonstrated by grid-feeding schemes, new potential for cost reduction will be tapped by serial manufacturing processes and learning effects forced by the routine implementation of projects under global market competition. The identification of yet undiscovered low-cost strategies is a natural element of technology convergence processes. In the course of the research, we identified the need to join forces and to strengthen stakeholder interaction to make use of the singular chance to establish marine energy in a commercial environment.

### 6.2. Technology-oriented stakeholders

#### 6.2.1. Competitive collaboration

Competitive collaboration is a form of strategic alliance between two or more independent firms that interact to pursue a set of agreed goals to contribute and share benefits on a continuing basis in one or more key strategic areas [30]. Hull and Slowinski [31] demonstrate that cooperative relationships in high technology between large industrial conglomerates (with strong market positions) and small firms (providing innovative technology) brought innovations to market that neither firm alone could have accomplished. If the marine energy industrial competitors accept the great significance of jointly achieving a long-term-oriented market success, then the motivation for entering into strategic alliances will rise.

#### 6.2.2. Detail and dynamic complexity

To ensure continuous progress towards competitive electricity generation, diverse problem-solving competences are required. In order to identify an optimum strategy before making a decision, the apparent problem complex needs to be analysed and categorised. There are technical difficulties that require profound engineering expertise, whereas other tasks – of more strategic nature – require qualitative assessment and tactical skills [32]. The complexity correlated with the market launch of marine energy can be subdivided into:

- a) Detail or combinatorial complexity (also referred to as complexity), which is characterised by many interacting elements and a large number of combinatorial possibilities. Apart from technology-related questions, detail complexity also appears within stakeholder-internal business management and in tasks of organisational nature. The application of complexity-reducing measures is expedient [33] and might favour: (i) applying systems engineering; (ii) forcing standardisation and certification; and (iii) using multi-applicable technologies.
- b) Dynamic complexity, which is characteristic for large-scale engineering and construction projects with multiple feedback-processes and non-linear relationships with accumulation or delay functions. Cause and effect can be subtle and obvious interventions can produce non-obvious consequences [34,35]. Concerning the process of marine energy commercialisation, dynamic complexity becomes apparent when looking at the long-term development history of the sector and the experienced setbacks. As a reduction of complexity can be counter-productive for dynamically complex tasks, qualitative feedback

modelling is seen as the preferred approach [33]. Within the present study, this was realised by means of system-dynamics-backed analyses of semi-structured expert interview data.

Research revealed that in conventional management, mainly aspects of detail complexity are considered but that the real leverage lies in understanding dynamic complexity [36]. Most industrial planning tools and analytical methods are not equipped to handle dynamic complexity [37].

#### 6.2.3. Competitive technology qualification routine

As years will pass before full maturity is reached, the introduction of a competitive technology qualification routine was proposed for early commercial projects in order to achieve the required safety for investment [38,39]. The principal idea is to complement the execution of large projects with a qualification process in the course of which different manufacturers' power conversion devices are deployed and operated under real-sea conditions in the final project area for a defined period of time. The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the main supply contract. Non-successful competitors are compensated. Competitive technology qualification routines would facilitate a transparent and evidence-based selection process to identify the most suitable technology for a specific site.

#### 6.3. Financing sector

Apart from the support for technologies with declared synergies toward off-shore wind, the financing sectors are expected to focus on stimulating the cross-interaction between the different forms of renewable energies and on strengthening design convergence. The cost of marine energy is seen as high compared to existing generation with hidden subsidies. As cost of energy was identified to be more relevant than capital expenditure, efforts are required to identify the techno-economic optimum way for the harvesting of marine energy. With regard to a mentioned need to compromise reliability and cost, the insurability of the projects must be ensured. In feasibility studies, it is important to consider that the cost of energy production is dependent on the capacity deployed [40]. In the course of a project planning, it is necessary to foresee extreme engineering and to consider the likelihood of test or early-stage failures. Pilot projects with availability records will provide confidence in the performance of the core technologies. Generally, it is required to keep in mind that realism is requested when it comes to the (global) scale of the industry and to recognise the differences to offshore oil & gas with regard to design, manufacturing and logistics.

#### 6.4. Policy framework

With regard to policy-related aspects, a key topic is to enable efficient consenting, leasing and licencing by ensuring a single point of handling. The close and regular adaptation of public support programmes and incentive mechanisms to actual requirements is crucial for accelerating the marine energy maturation process. The need to bring in existing skills from the oil & gas sector, to improve knowledge sharing and to strengthen collaboration between industry, utilities, academia, device manufacturers and project developers was identified. The implementation of appropriate risk sharing mechanisms between the stakeholders is relevant for achieving common progress. In order to prepare the move from device testing towards array-scale activities under open sea conditions, grid-connected test facilities and pilot zones are of high value. Considering future large-scale

deployments, the importance of transmission infrastructure investments and support strategies for grid operation with significant wave and tidal in-feed cannot be underestimated. With regard to the global scale of the industry, simplified access to the international (out of Europe) markets is important.

## 7. Conclusion

The approach of using cross-category expert interview data to create system dynamics computer models is seen as a powerful method to keep track of the sectorial development and thus to advance strategy finding.

The two major risks for multi-megawatt projects (funding and device performance) are directly interlinked and co-ordinated action is required to overcome this circular relationship ("chicken or egg causality dilemma"). As funding is required for improving device performance (and vice-versa), showcasing an array-scale success was identified as the interim milestone on the way towards commercial generation. This game-changing event will simultaneously mitigate both mentioned risk complexes. With the near-future prospect of realising profits in a new power market segment, there should be a strong motivation for cooperative industry interaction aimed at jointly de-risking the technology.

To fulfil both requirements, i.e. (i) to achieve the market breakthrough; and (ii) to establish a new industry with a variety of manufacturers, extraordinary concessions between natural competitors are required. The (temporary) joining of forces in the form of competitive collaboration is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence. It shall be remembered that the available incubation rooms were created with the goal of developing the technology to the level of reliability required to compete in the energy market. A special level of collaborative behaviour in a test field environment is beneficial to the sector.

Referencing to the initial hypothesis, the paper makes the following contribution:

*The presented target-oriented measures are suitable to support the commercialisation of marine energy on a fundamental level. The combination of expert interview data and system dynamics modelling allows the identification of effective and practically implementable strategies.*

The most comprehensive and strategically demanding task is to attract financing and to successfully embed the innovative generation method into the energy infrastructure. To be able to adapt to a continuously changing socio-technical environment, evolutionary steering mechanisms and systemic thinking are required. The chosen strategy must be flexible and re-adjustable to new trends and priorities.

## Acknowledgements

The study is part of a PhD research into strategic risk management for marine energy projects at the Institute for Energy Systems, University of Edinburgh, UK. The authors are grateful to the interview participants and the anonymous reviewers for providing helpful suggestions.

## References

- [1] Strategic Initiative for Ocean Energy, Wave and Tidal Energy Market Deployment Strategy for Europe, Co-funded by the Intelligent Energy Europe Programme of the European Union, 2014, <http://si-ocean.eu> [19/06/2015].
- [2] S. Leete, et al., Investment barriers and incentives for marine renewable energy in the UK: an analysis of investor preferences, *Energy Policy* 60 (2013) 866–875.
- [3] A. Masini, E. Menichetti, The impact of behavioural factors in the renewable energy investment decision making process: conceptual framework findings, *Energy Policy* 60 (2012) 28–38.

- [4] D. Magagna, A. Uihlein, Ocean energy development in Europe: current status and future perspectives, *Int. J. Mar. Energy* 56 (2015). <http://dx.doi.org/10.1016/j.ijome.2015.05.001>.
- [5] Department of Energy & Climate Change, Renewable Energy Roadmap, UK, 2011.
- [6] IEA-OES, Annual Report, Spain, 2013, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2014].
- [7] M. Previsic, et al., The Future Potential of Wave Power in the US, American Geophysical Union, 2012. Fall Meeting 2012, abstract #OS53D-08, [www.revision.net](http://www.revision.net) [06/04/2014].
- [8] RenewableUK, Wave & Tidal Energy, 2013. [www.renewableuk.com](http://www.renewableuk.com) [13/02/2013].
- [9] Fraunhofer-ISE, Levelised Cost of Electricity, Renewable Energy Technologies, 2013. [www.ise.fraunhofer.de](http://www.ise.fraunhofer.de) [06/04/2013].
- [10] International Renewable Energy Agency, Renewable Energy Technologies: Cost Analysis Series, 2012. [www.irena.org](http://www.irena.org) [10/04/2014].
- [11] M. Previsic, K. Shoel, Cost Reduction Pathways for Wave Energy, 10th European Wave and Tidal Energy Conference, Aalborg, Denmark, 2013.
- [12] IEA-OES, Ocean Energy Review of Supporting Policies, 2014. [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2013].
- [13] IEA, Technology Roadmap Wind Energy, 2013. [www.iea.org/publications](http://www.iea.org/publications) [06/05/2014].
- [14] K.A. Karikari-Boateng, et al., Reliability of Tidal Turbines Using Wind Turbine Experience (Proceedings of the European Wave and Tidal Energy Conference, Aalborg, Denmark), 2013.
- [15] B. Carlsson, et al., Innovation systems: analytical and methodological issues, *Res. Policy* 31 (2002) 233–245.
- [16] F.W. Geels, From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory, *Res. Policy* 33 (2004) 897–920.
- [17] F. Alkemade, C. Kleinschmidt, M. Hekkert, Analysing emerging innovation systems: a functions approach to foresight, *Int. J. Foresight Innov. Policy* 3 (2007) 139–168.
- [18] S.O. Negro, et al., Why does renewable energy diffuse so slowly? A review of innovation system problems, *Renew. Sustain. Energy Rev.* 16 (2012) 3836–3846.
- [19] B.A. Andersson, S. Jacobsson, Monitoring and assessing technology choice: the case of solar cells, *Energy Policy* 28 (2000) 1037–1049.
- [20] R.R. Nelson, Understanding technical change as an evolutionary process, *J. Econ. Behav. Organ.* 11 (3) (1989) 450–453.
- [21] S. Steinhilber, P. Wells, S. Thankappan, Socio-technical inertia: understanding the barriers to electric vehicles, *Energy Policy* 60 (2013) 531–539.
- [22] A. Bergek, M. Hekkert, S. Jacobsson, Functions in Innovation Systems: a Framework for Analysing Energy System Dynamics, Institute for Management of Innovation and Technology, 2008. Working Paper No. 84426–008.
- [23] W.B. Erickson, I. Maitland, in: M.E. Dutton (Ed.), *Healthy Industries and Public Policy*, Pergamon Press, New York, 1989.
- [24] F.W. Geels, R. Kemp, Dynamics in socio-technical systems: typology of change processes and contrasting case studies, *Technol. Soc.* 29 (4) (2007) 441–455.
- [25] G.A. Okhuysen, K.M. Eisenhardt, Integrating knowledge in groups: how formal interventions enable flexibility, *Organ. Sci.* 13 (4) (2002) 370–386.
- [26] J.C. Huang, S. Newell, Knowledge integration processes and dynamics within the context of cross-functional projects, *Int. J. Proj. Manag.* 21 (2003) 167–176.
- [27] M. Formentini, P. Romano, Using value analysis to support knowledge transfer in the multi-project setting, *Int. J. Prod. Econ.* 131 (2011) 545–560.
- [28] R. Bucher, H. Jeffrey, The Strategic Objective of Competitive Collaboration: Managing the Solid Market Launch of Marine Energy, 11th European Wave Energy Conference, ISSN 2309–1983, Nantes, France, 2015.
- [29] B. Jay, H. Jeffrey, UKERC Research Atlas Topic: Marine Energy, UK Energy Research Centre, London, 2010.
- [30] M.Y. Yoshino, U.S. Rangan, *Strategic Alliances: an Entrepreneurial Approach to Globalization*, Harvard Business School Press, Boston, USA, 1995.
- [31] F. Hull, E. Slowinski, Partnering with Technology Entrepreneurs, *Research Technology Management* (11/12), 16–20, 1990.
- [32] R. Bucher, I. Bryden, Strategic orientation for ocean energy market roll-out: coherent technology learning by system dynamics modelling of trans-organisational expert knowledge, *J. Energy Chall. Mech.* 1 (2) (2014) 1–10. ISSN 2056-9386.
- [33] S. Groesser, Projects fail because of dynamic complexity: managing complexity by qualitative feedback modelling, *Proj. aktuell* 22 (5) (2011) 18–25. Bern University of Applied Sciences, Switzerland.
- [34] J.D. Sterman, *System Dynamics Modelling for Project Management*, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, 1992.
- [35] K. Cooper, G. Lee, *Managing Dynamics of Projects and Changes*, International System Dynamics Conference, USA, 2009.
- [36] J.D. Sterman, Does formal system dynamics training improve people's understanding of accumulation? *Syst. Dyn. Rev.* 26 (4) (2010) 316–334.
- [37] P. Senge, *The Fifth Discipline: the Art and Practice of the Learning Organisation*, ISBN 978-0553456349, Crown Publishing Group, New York, , 1990.
- [38] R. Bucher, I. Bryden, Overcoming the marine energy pre-profit phase: what classifies the game-changing “array-scale success”? *Int. J. Mar. Energy* (2015). ISSN 2214-1669, <http://dx.doi.org/10.1016/j.ijome.2015.05.002>.
- [39] R. Bucher, I. Bryden, Governing the market entry of marine energy by symptom-adapted interventions: (i) reduction of detail complexity; and (ii) managing dynamically complex tasks, *J. Energy Challenges Mech.* 2 (2) (2015) 56–61 article 4, ISSN 2056-9386, North Sea Conference & Journal, Aberdeen, UK, <http://dx.doi.org/10.13140/RG.2.1.2946.3760>.
- [40] R. Bucher, S.J. Couch, Adjusting the financial risk of tidal current projects by optimising the “installed capacity/capacity factor”-ratio already during the feasibility stage, *Int. J. Mar. Energy* 2 (2013). ISSN 2214-1669, <http://dx.doi.org/10.1016/j.ijome.2013.05.008>.

## **F Publications**

### **F.1 Scientific journal articles**

Bucher, R., Bryden, I.G. (2016) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, International Journal of Marine Energy, in press (corrected proof), <http://dx.doi.org/10.1016/j.ijome.2015.05.002> (originally presented at the 2<sup>nd</sup> Asian Wave and Tidal Energy Conference, 2014, Tokyo, Japan)



Contents lists available at ScienceDirect

International Journal of Marine Energy

journal homepage: [www.elsevier.com/locate/ijome](http://www.elsevier.com/locate/ijome)



# Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?



Ralf Bucher<sup>a,\*</sup>, Ian Bryden<sup>b</sup>

<sup>a</sup> University of Edinburgh, Institute for Energy Systems, Mayfield Road, Edinburgh EH9 3JL, UK

<sup>b</sup> University of the Highlands and Islands, Ness Walk, Inverness IV3 5SQ, UK

## ARTICLE INFO

### Article history:

Received 18 September 2014

Revised 17 May 2015

Accepted 29 May 2015

Available online 5 June 2015

### Keywords:

Marine energy commercialisation

Creation of investor confidence

Array-scale success

System dynamics modelling

## ABSTRACT

Tidal current and wave power have made substantial progress towards commercialisation. Based on the successful testing of full-scale prototypes, pioneering tidal arrays are currently implemented by means of direct agreements between developers/investors and device manufacturers. The top-ranked risks for commercial projects (identified as *achieving funding* and *uncertainty in device performance*) are directly intercorrelated as investor confidence mainly depends on track records of continuous device operation. Before becoming recognised as a fully mature electricity generation method, marine energy needs to prove a range of referenceable project cases. The attainment of this *array-scale success* will represent a major turning point for the global marine energy business and is expected to finally trigger large-scale deployment.

© 2015 Elsevier Ltd. All rights reserved.

## 1. Introduction

Marine renewable energy arises in an era of global interest in carbon-free electricity generation. After significant technological advances in the wave and tidal sector in the last years, the industry is now moving from full-scale prototype testing to the phased implementation of the first tidal arrays ranging from 5.6 to 86 MW [1–3]. These demonstration projects are mainly based on bilateral agreements between developers/investors and leading device manufacturing firms. The

\* Corresponding author. Tel.: +49 157 72943159.

E-mail addresses: [r.bucher@sms.ed.ac.uk](mailto:r.bucher@sms.ed.ac.uk) (R. Bucher), [ian.bryden@uhi.ac.uk](mailto:ian.bryden@uhi.ac.uk) (I. Bryden).



global potential of marine energy and the planned investments are substantial. In the UK, The Crown Estate has leased 37 wave and tidal sites with a total capacity of 1800 MW [4]. The UK Department of Energy and Climate Change stated that up to 300 MW of generation capacity might be deployed by 2020 [5]. For the period up to 2050, installation capacities in the multi-gigawatt range are indicated [6].

Taking into consideration these figures and the projected machinery ratings, the number of devices to be tendered, deployed and operated will be in the range of several thousands. According to RenewableUK, presently, 12 full-scale devices with a total output of 9 MW are undergoing sea trials in UK waters [7].

In the course of this research, the interviewed experts provided estimations for risk levels focusing on the realisation of virtual tidal current or wave power reference projects (capacity ~40 MW, implementation ~2025, investment ~120 m€). The top-ranked risks were identified as *achieving funding and reliability* (i.e. *uncertainty in device performance*).

## 2. Objective of the research

Considering a business environment in which other renewables operate price-competitive to conventional sources and the appearance of new forms of hydrocarbon extraction, the market entry of marine energy is seen as a one-off chance. To enhance the success rate, stakeholder-wide co-ordination and collaborative interaction are required. The top-level driving factors for achieving full-commercial power generation by marine energy were determined by Bucher [8] in the course of a system dynamics-backed analysis of cross-category expert interview data as (i) *strong and long-term commitment from government*, (ii) *array-scale success*, and (iii) *cost reduction*.

As the singular characteristics of government regulations are outside the range of this research, focus is put on the interim milestone *array-scale success*. The effective preparation and conduction of this game-changing task is seen as the decisive strategic objective at this time.

The research is oriented around the hypothesis:

*“Regular commercial marine energy array projects will be realised under institutional financing and according to international procurement principles. To ensure investor confidence, the reliability of the technological concept has to be proven in advance. The application of co-ordinated strategic principles, identified in the course of expert interviews and by system dynamics analyses, facilitates achieving the array-scale success which represents the key interim milestone towards commercialisation.”*

To rapidly overcome the present pre-profit phase, the strategic orientation of all active stakeholders needs to be regularly evaluated in order to identify joint objectives and to put corresponding measures into practice. Ideally, the future supplier market will be composed of numerous manufacturing companies offering comparable high-class technology under competitive pricing.

## 3. Research principle and methodology

The underlying idea for our research approach is inspired by a strategic rule known in the theory of games as *look ahead and reason back* [9]. In the present context, *look ahead* is defined by focusing on the reason for the existence of any large-scale power scheme – market competitive electricity generation – and in this case by marine energy. A main principle applied is to comprehensively integrate a wide spectrum of stakeholder positions in a transparent and unbiased and manner based on system dynamics modelling techniques. This multi-disciplinary attempt allows an all-encompassing appraisal by avoiding concentrating in a limiting manner on stakeholder-specific views or interests.

For the survey, a four-page questionnaire with a total of 90 questions was elaborated, out of which 48 were yes/no questions and 42 were of a qualitative character, referring to stakeholder-related experience. By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks, out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. Two received questionnaires had to be discarded because they were rather

**Table 1**

List of participating stakeholders.

---

<i>Government (associations) &amp; trade organisation:</i>	The Scottish Government (UK), Marine Scotland (UK), Energy Technologies Institute (UK), Carbon Trust (UK), Department of Energy and Climate Change (UK), The Crown Estate (UK), Scottish Natural Heritage (UK), Centre for Environment, Fisheries & Aquaculture Science (UK), RenewableUK (UK), Technology Strategy Board (Ireland)
<i>Certifying authorities:</i>	Det Norske Veritas (UK), Lloyd's Register (UK)
<i>Investors &amp; lenders:</i>	Green Giraffe (UK)
<i>Law firm:</i>	Eversheds International (UK)
<i>Academia &amp; research:</i>	University of Washington (USA), University of Edinburgh (UK), National Taiwan Ocean University (Taiwan), Irish Marine Institute (Ireland)
<i>Engineering consultancies:</i>	Natural Power (UK), Xodus Group (UK), Tecnalia Research & Innovation (Spain), South West Renewable Energy Agency (UK), Royal Haskoning (UK)
<i>Project developers:</i>	Emera (Canada), EDF (France), Electricity Supply Board (Ireland), Iberdrola (Spain)
<i>Owners &amp; operators:</i>	ScottishPower Renewables (UK), Ente Vasco de la Energía (Spain)
<i>Transmission system operator:</i>	Scottish and Southern Energy Renewables (UK)
<i>Device manufacturers:</i>	Marine Current Turbines (UK), Pelamis Wave Power (UK), Wavebob (Ireland), Siemens (Germany), Wave Star (Denmark), Ocean Renewable Power Company (USA)
<i>Offshore contractors:</i>	6 contacted (no feedback)
<i>Test site operators:</i>	European Marine Energy Centre (UK), Fundy Ocean Research Centre for Energy (Canada), National Renewable Energy Centre (UK), Minas Basin Pulp & Power (Canada), France Energies Marines (France)
<i>NGO:</i>	Greenpeace (UK)
<i>Offshore wind industry:</i>	Dong Energy Power (UK)
<i>Oil &amp; gas industry:</i>	4 contacted (no feedback)

---

incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups (see Table 1) was retained for the analysis, corresponding to an effective return rate of 32.4%, which is more than the usual number for studies of this nature [10]. A total of 2129 individual replies had to be grouped to formulate higher-level correlations as a basis for the computer-based system dynamics modelling. All semi-structured single person interviews were conducted either face-to-face at the premises of the interviewee or by telephone between June 2012 and April 2013.

Our contribution aims to streamline the dynamic interplay between trans-organisational knowledge collection, system dynamics-backed information compression and the targeted diffusion of strategic know-how.

#### 4. The game-changing “array-scale success” and its conclusive effects

##### 4.1. Definition of the term and salient features

Marine energy finds itself in a decisive transition phase with successfully tested full-scale prototypes but an outstanding utility-scale proof of the technological concept. In the course of the expert interviews, the importance of focusing on *array-scale activities* and getting *pilot farms built* was repeatedly stressed. Most answers to the question “*In which areas is research most required to accelerate the development of marine energy?*” referred directly to topics regarding multi-device arrangements such as *array-scale design*, *hydrodynamic modelling of arrays*, *array-scale maintenance*, the need for *design tools to facilitate cost-effective array-scale development* and to see *first arrays progressing through FID*<sup>1</sup>.

The following aspects were identified as highly sensitive to the success of marine energy: lack of investor confidence, fragmented initiatives by inexperienced parties, technology failures and critical events regarding health and safety (negative press). These factors underline the importance of showcasing commercial-scale projects and successful demonstrators in order to improve the credibility of the generation method and thus to create a positive investment climate.

Before becoming recognised as a fully mature and competitive electricity generation method, marine energy needs to prove a range of referenceable application cases. The attainment of the

<sup>1</sup> Final Investment Decision (reference is made to the 2013/2014 DECC report *Final Investment Decision Enabling for Renewables*).



confidence-building *array-scale success* will represent a major turning point for the global marine energy business as it is expected to finally trigger large-scale deployment. Because of the comprehensive demands on this milestone, the hurdle will not be passed by a small number of companies in the course of a singular demonstration project at one specific site.

*Array-scale success* represents the key interim milestone and has to be seen within the larger picture as characteristic of the global power sector. For a marine energy technology breakthrough, positive and transparent feedback from a variety of longer term grid-connected, commercially operated multi-device arrays is required. In case the first small-scale arrays become operational in 2016/17 as outlined in [7], then the achievement of *array-scale success* as per definition can be expected in the first half of the new decade.

#### 4.2. Creation of investor confidence

Leete et al. [11] performed a series of interviews with senior finance and industry actors in the marine renewables sector and examined investor attitudes towards wave and tidal technologies. They reported that none of the four investors previously engaged in venture capital funding of early stage marine energy device development in the UK were likely to do so again. Venture capital investors are discouraged from investing because of high capital requirements and the uncertainty of costs, respective of future revenues. It is outlined that a track record of continuous device operation of at least six months is seen as a pre-requisite for further investments. The authors conclude that, at the current stage of development, strategic investment in partnership with industry investors is essential for moving towards commercialisation.

Investors profiled by Masini and Menichetti [10] show a clear preference for more mature, proven technologies with only three of the 93 investors analysed having any exposure to wave and tidal energy. Given the small scale of current marine energy developments, investors are able to achieve similar or greater returns on larger developments of more proven energy technologies.

According to Sjöö [12], the following is usually assessed before venture capital investment in renewable energy technologies: regulatory framework, competitive situation, technological risks, market uncertainty and supply chain constraints. Santos et al. [13] emphasise that energy investments have specific characteristics because of (i) their irreversibility, (ii) high levels of uncertainty, and (iii) flexible timing, as the investor might be able to postpone his decision in order to obtain better information. The different funding sources regarding the technology development and maturation stages are summarised by Wüstenhagen [14] as grants (for R&D), venture capital (for part-scale prototypes), private equity (for full-scale prototypes), debt finance (for first pioneering arrays), and institutional finance (for utility-scale projects).

Aside from the difficulty of venture capitalists engaging, private company investment in marine energy of over 600 m€ since 2006 has built confidence and triggered significant progress [15]. The involvement of major industrials (ABB, Alstom, Andritz, DCNS, Lockheed Martin, Siemens<sup>2</sup> and Voith<sup>3</sup>) as well as the successful testing of full-scale prototypes underline the commitment in the sector and indicate significant accessible engineering competence.

#### 4.3. Project certification to confirm market-readiness

Reliability is an important factor of success for all emerging technologies. In marine energy, reliability proof remains a major challenge as most devices to date have been in the water only for short periods of less than one year. Reference data is, therefore, limited. In contrast to offshore wind, tidal current and wave power technology development cannot benefit from the extension of reliable

<sup>2</sup> In February 2012, Siemens acquired a majority share in the tidal device manufacturer Marine Current Turbines (MCT). Since November 2014, Siemens has been looking to exit the marine energy sector, saying the development of the market and the supply chain has taken longer to grow than expected. In April 2015, Atlantis Resources Limited announced that it has reached agreement to acquire the entire issued share capital of MCT from Siemens.

<sup>3</sup> In March 2013, Voith Hydro decided to shut down its wave power business (Wavegen), choosing to concentrate on tidal power. A spokesman outlined that Voith will re-intensify its wave power activities as soon as the market situation is appropriate.

onshore devices. Without any transition period, the maturity of the power machinery equipment and related systems has to be proven directly under harsh marine conditions in high-energy sites.

In mature industries, third-party certification is well established. This means that an independent organisation confirms the compliance of a product or service with legal-normative standards, contractual obligations or project-specific requirements. The European Marine Energy Centre [16] lists two kinds of certification: type and project certification. Type certification refers to a marine energy converter built in serial production or to the parts of it. It consists of an assessment of the quality management system and an evaluation of compliance with contractual requirements in the production, manufacturing, deployment and commissioning phases as well as during operation. Within a project certification, it is assessed whether the respective site conditions (e.g. meteorological and oceanographic data, soil properties, environmental aspects and electrical network data) conform to those defined in the contract specification. According to the authors, a project certificate refers to the design (and changes thereof), manufacturing, installation and commissioning of a marine energy farm, including cable laying and grid connection. In the context of proving *array-scale success*, an integrity assessment of the technological concept – and, as such, type and project certification – are required. Conformity certificates will be issued for the constituent projects.

In the course of the performed interviews, a classification society representative underlined the importance of standardisation and certification. He emphasised the need to accelerate the development of robust and reliable marine energy technology and recommended to carefully balance progress with a level of risk acceptable to all involved stakeholders.

In public procurement processes, bidders need to fulfil minimum qualification criteria. In the case of marine energy, for device manufacturers, the following serve as evidence of conformity: (i) previously installed converters (type, rating, marine climate, foundation type, grid interface, distance to shore), (ii) geophysical and geotechnical conditions, (iii) environmental impact assessment, (iv) operation and maintenance protocols, (v) a health and safety log, and (vi) confirmed CapEx<sup>4</sup> and OpEx<sup>5</sup> data.

#### 4.4. Developing a market by manufacturer competition

As from a long-term perspective, the marine energy industry sector might become principally comparable to that of wind power, the development of the number of megawatt wind and tidal stream turbine manufacturers – including the respective globally installed capacities in GW<sup>6</sup> – are depicted in Fig. 1 from 1970 to 2015.

It is encouraging to note that, in marine energy, the first 1 MW full-scale prototype was deployed in the year 2008, and, only seven years later, there are at least six renowned manufacturing companies providing comparable equipment. In this regard, the momentum for growth in marine energy is significantly higher than it was for wind power where this development required about 16 years. In the year 1986, for wind power, a significant annual capacity increase of about 400 MW was realised within a global market environment of only six competing MW-turbine manufacturing firms [17–20].

Today, full-scale 1 MW + tidal stream horizontal-axis converters are manufactured by major industrial companies such as: Alstom (Oceade), Andritz Hydro Hammerfest (HS1000), Atlantis Resources Limited (AR1000 and former Siemens/MCT SeaGen), DCNS (Open-Centre), Voith Hydro (HyTide 1000) and Scotrenewables (SR2000). Wave energy converters of 500 kW + rating are produced by: Aquamarine Power (Oyster), AWS Ocean Energy (AWS-III), Seatricity (Oceanus) and Wello Oy (Penguin), among others [21].

Apart from public marine energy support regimes to help commercialise tidal and wave technologies, strategic partnerships between major utilities and leading device manufacturers are currently in place. By jointly financing and managing projects, the transition from single-device testing towards commercial-scale array deployment is streamlined and the correlated risks are shared.

<sup>4</sup> Capital expenditures: pre-development costs, construction costs, electrical system infrastructure costs.

<sup>5</sup> Operational expenditures: operating and maintenance costs, insurance costs, de-commissioning costs, seabed lease, transmission grid charges.

<sup>6</sup> 1 Gigawatt [GW] = 1000 Megawatt [MW] = 1,000,000 Kilowatt [kW].

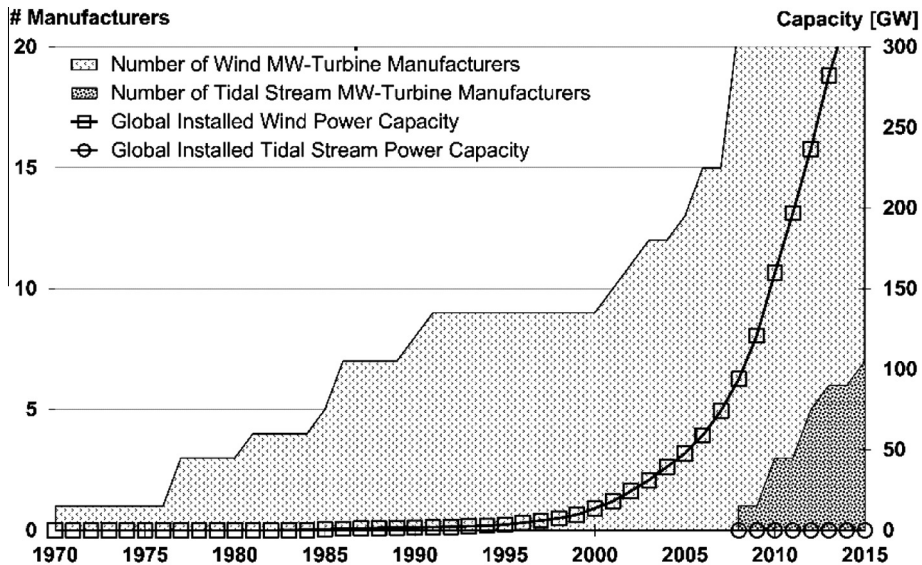


Fig. 1. Comparing the development of wind and tidal stream power: number of manufacturers and capacity installed.

Current examples of such partnerships are:

- (i) ScottishPower Renewables has received consent to construct and operate the 10 MW *Sound of Islay demonstration tidal array electricity generating station*. The ten 1.0 MW candidate devices are supplied by Andritz Hydro Hammerfest, and installation is planned to start in 2016 [22].
- (ii) MeyGen Limited was granted a marine licence for the *Inner Sound project in the Pentland Firth* in 2014 [23]. Funding was secured for the first stage of the project, which will comprise the installation of four 1.5 MW turbines (three will be supplied by Andritz Hydro Hammerfest and one by Atlantis Resources Limited) [24].
- (iii) GDF SUEZ will install four Alstom tidal turbines with a total output of 5.6 MW at the *tidal energy pilot farm at Raz Blanchard* in France. Construction of the scheme is scheduled to begin in 2017 [25].

It is noteworthy that, in the conventional power sector, such direct collaborations would be hindering and not in line with current regulations for projects realised under international competitive bidding (ICB<sup>7</sup>). The probability of getting the best-available technology at a market-balanced price would be critically reduced.

#### 4.5. Continuous up-scaling or a twin-track technology development strategy?

In wind power, for decades, we have noticed continuous innovation and a steady increase of the standard turbine rating. From 1984 until today, the rotor diameter has increased from 15 to 164 m and the nameplate rating from 50 kW to 8 MW [26]. The next development step in offshore wind is expected to be the introduction of 15 MW turbines [27]. In the course of a European Commission financed research programme (FP6), it was found that the design of very large wind turbines up to 20 MW would require technological step changes but is considered as principally feasible [28].

In the tidal stream sector, we find a less coherent development. Even as the main focus of major industrials is presently on 1 MW + demonstrator devices, a number of tidal developers

<sup>7</sup> ICB refers to the selection of the lowest-priced bid under fair and healthy international competition.

(e.g. Schottel, Nova Innovation and Tocardo) follow a distinctly different approach by working on small-scale technologies (30–500 kW) in order to reduce both the costs and risks associated with manufacturing, testing and deployment [29]. In a comprehensive report on gaps and barriers to ocean energy technologies [21], it is emphasised that a twin-track development strategy is necessary: (i) large-scale devices to raise the credibility of the sector and to ensure that EU deployment capacity targets are met, and (ii) small-scale technologies to allow a rapid expansion and proving of early arrays, thus complementing the overall approach of learning-by-doing. To cover a wide range of potential tidal sites and to suit different project budgets, both large-scale and small-scale devices are necessary. Independent of nameplate capacity, for the market breakthrough, it is required to achieve transparent *array-scale success* with a number of long-term grid-connected devices.

#### 4.6. Triggering serial production and cost reduction

After the concept maturity will have been demonstrated by grid-feeding demonstrator schemes, new potential for cost reduction will become accessible by serial manufacturing processes and due to learning effects driven by the routine implementation of projects under global market competition. Furthermore, the identification of yet undiscovered low-cost strategies is expected as a natural element of the technology convergence process.

According to DECC [5], the projected levelised cost of electricity generation (LCOE<sup>8</sup>) for UK marine energy in the year 2020 will range between 20 and 42 ¢/kWh. Spain expects LCOE for that period of time of 21–33 ¢/kWh [30]. Previsic et al. [31] have pointed in a similar manner to a commercial opening cost of electricity for wave power in the order of 20–30 ¢/kWh. Until 2020, DECC projects LCOE for onshore wind in the UK of 9–15 ¢/kWh and projects LCOE for offshore wind of 13–22 ¢/kWh. RenewableUK [7] believes that the current LCOE for leading tidal stream devices is around 36 ¢/kWh, compared to 48 ¢/kWh for wave power devices.

As onshore wind energy represents the reference for cost-competitive renewable power, it should be noted that global average LCOE dropped from 19 ¢/kWh in 1992 to 6 ¢/kWh in 2014 [32]. Offshore wind farms at very good locations currently achieve LCOE of 11–19 ¢/kWh [33,34].

Presently, the kWh-costs in marine energy are far too high for the sector to compete with other renewable or even non-renewable generation options [35]. Taking into consideration the projected LCOE in the UK for 2020, the cost for tidal stream might touch the upper end of the offshore wind range. For the forthcoming years, governmental support programs will be indispensable to drive further research and development [36]. Referring to offshore wind – with a global installed capacity of 5.4 GW [37] – it is expected that 15 years of further subsidies will be required [38].

Apart from purely assessing LCOE values, it needs to be evaluated to what extent a grid-integrated renewable power system affects the operational characteristics of an existing network. Electricity generation by tidal currents is – contrary to the case of infeed by wind and photovoltaic systems – predictable in the long-term due to the known effects of gravitation exerted by the moon (68%) and the sun (32%) upon the earth. Tidal regimes are determined by almost 400 harmonic components, which makes it necessary to consider a complete synodic month (29 days, 12 h, 44 min) for one periodic repetition cycle. As the corresponding semi-diurnal tidal cycle of about 12.5 h is out of phase with diurnal public power consumption, balancing capabilities are required. Grid stabilisation can either be realised by additional generation/consumption (e.g. pumped hydro) or by grid expansion [39]. Intermittent infeed is especially critical at remote sites where a weak grid connection could become an economically relevant factor. In case of an off-grid hybrid system with a combination of wind, solar photovoltaic and reserve-capacity (bio) diesel generation, the precisely predictable tidal contribution can be integrated into the basic operational regime.

<sup>8</sup> LCOE is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.

## 5. Strategic principles for rapidly achieving the “array-scale success”

### 5.1. Systems engineering approach

When asked about significant potential to lower the cost for utility-scale project implementations, the CEO of an Irish wave energy converter manufacturer emphasised the clear recognition to orientate the development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. The vice president of a multi-national engineering conglomerate underlined in a similar manner the importance of proving that systems work reliably and consequently focusing on end-user requirements. These statements correlate with the central objective in systems engineering, which is to consider a finally envisaged functionality already in the early project stages. An important element in the design and implementation process of complex technological systems is to perform regular system functionality checks. Finally, marine energy converters have to operate for the long term in open sea grid-connected multi-device arrays.

### 5.2. Multi-applicable technologies and joint concepts

According to the opinion of a utility ocean energy project manager, one of the top-priority tasks in the work of academia and research should be to concentrate on multi-applicable technologies and standardised devices and components (e.g. moving parts, nacelle, foundations, electrical system, protection, controls). The benefit by working along a robust engineering plan targeting serial production and large-scale manufacturing was underlined. To finally ensure identical component design and delivery, effective supply chain management and leveraging logistics are required. Referencing offshore wind, in [40] it is pointed out that joint installation and maintenance concepts for adjacent wind farm locations significantly increased the installation and operation efficiency.

### 5.3. Standardisation (look at volume manufacturing)

The reply of a project developer's head of offshore operations when asking for the most valuable experience gained by the *early movers*, was the *experienced negative impact of missing standardisation*. Considering the urgent need for consensus over standardisation, one interviewee referred to a detected over-engineering in oil and gas standards (with regard to marine energy purposes). A marine renewables engineer employed by an energy consulting firm identified *consensus over standardisation* as a target that appeared more difficult to reach than originally planned. One interviewee summed up the situation as *no standards, no results*. The overall importance of standardisation in marine energy was emphasised by several interviewees who highly appreciated the published results of a standardisation group within one of the top three certification companies. The date of publishing new technical standards and the level of detail need to be carefully discussed with manufacturing companies to avoid early-stage limitations on non-published but promising R&D projects and unnecessary cost increase. A senior contracts expert of an international law firm mentioned the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms). Contract splitting (e.g. in foundation, turbine, inner-park cabling, transformer station, power take-off) as in offshore wind was recommended.

### 5.4. Technology convergence

The emergence of dominant designs in complex technical environments was examined by Murmann and Frenken [41] from a system theory perspective under the aspect of technology standardisation. As marine energy innovation activities are spread over a wide variety of concepts and components, a lack of design consensus is likely to restrict the pace of development and learning [42]. On the other hand, Jacobsson and Bergek [43] emphasise potential longer-term advantages by retaining design variety. In the course of the performed interviews, two main philosophies characterising technological advancement were detected: *incremental innovation* and *radical innovation*. With a

focus on technology convergence in marine energy, Jeffrey et al. [44] emphasise the need for supporting both incremental and radical innovation in parallel. Incremental innovation is relevant for closest-to-market full-scale prototypes, and radical innovation is relevant for technologies with a potential for step-change performance improvements. In a research project on product development by Augustine et al. [45], it was concluded that a robust approach for systematic improvement is to combine the strengths of all available concepts instead of selecting the best among alternatives. Kaplan and Tripsas [46] describe how the evolution of technology is influenced by institutional actors (such as government agencies, the media, standardisation bodies, industry associations) and outline that, in a case where a *collective technological frame does not emerge*, convergence on a dominant design might be prevented. Teece [47] describes that, once a dominant design has emerged, competition shifts to a whole new set of parameters of which the most important one is cost. In the IEA report *Scenarios and Strategies to 2050* [48], it is emphasised that the initially higher cost of new technologies can only be reduced through technology learning as a result of marketplace deployment.

### 5.5. Knowledge sharing and knowledge transfer

Limited knowledge sharing in industry is seen by the strategy manager of a public–private partnership and the head of energy of a governmental innovation agency as a main reason why the marine energy sector has not developed more rapidly. A senior policy officer underlined the need to transfer lessons learnt in the offshore wind industry to marine energy in order to avoid duplication of time and effort. According to the vice-chair of a large private R&D group, the transfer of knowledge from other sectors (under consideration of the specific aspects of marine energy) is identified as a top-priority task in the commercialisation process. The project manager for the implementation of a commercial breakwater wave power plant outlined that the need to improve the sharing of bad (!) experiences and testing data is key. According to his commissioning experience, sometimes, unspectacular and cheap items created unexpected difficulties. To support progress, his position is to inform (as far as possible) about such complications at conferences, explain why things went wrong and display the finally implemented solution.

### 5.6. Maximising collaboration and minimising competition

In line with the findings on the limited sharing of knowledge, a lack of collaboration in the industry was reported. Apart from improving co-operation, a strengthening of the interaction between device manufacturers and engineering consultancies companies was called for. The head of policy of a major developer emphasised the expected benefits of enhanced collaboration among individual project agencies. With regard to academia, he mentioned the need to intensify international collaboration. The artificial competition with on-/offshore wind was criticised by an Irish ocean energy development manager as negatively influencing an uninterrupted progress. A chance to improve cross-interaction among renewable energies is seen in identifying the prospective synergy effects of inter-coupling different kinds of carbon-free generation methods. The interviewed head of development of a wave energy device manufacturer, which recently entered into a research and development collaboration with a major offshore wind developer, underlined the attractiveness of exploring the prospects of combining wave and wind power. Seeking synergies with other manufacturers considering the use of similar technology is seen as a natural process. The experienced increasing involvement and interaction with major industrials in the ocean energy sector is seen as positive and will help to restructure the supply chain. Amanatidou and Guy [49] emphasise the increasing importance of knowledge-based industries and focus on research into aligning existing perceptions by maximising collaboration and minimising competition.

### 5.7. Inter-firm alliances and strategic co-operations

Marine energy needs to assert its position in the highly competitive (renewable) energy market. Exemplary strategic alliances regarding how to develop new products and to penetrate new markets can serve as a reference. In a recently published paper from the European Ocean Energy Association



[15], clear reference was given to Airbus, which was classified as a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments. In the global automotive industry, we can see a tendency towards strategic co-operation in the course of the development and market introduction of electric vehicles. As the goal in this sector is to create a common infrastructure to allow the vehicles go to mass market, some manufacturers treat patents as open source and invite competitors to share their technology.

#### 5.8. Contractually optimised risk sharing

The development manager of a wave energy converter manufacturer explained that his company's approach towards risk management is to collaborate with a multi-national oil and gas exploration corporation. He stressed the requirement to share risks through collaboration and to fully integrate risk management into project management. An interviewed law firm contracts expert highlighted that risk sharing should be contractually optimised to identify the most appropriate risk owners. Experience in negotiating risk sharing is seen as a valuable outcome by the activities of front-running companies. An owner's representative recommended that engineering consultancies should share risk with project developers. The implementation of appropriate risk sharing between stakeholders is seen as essential for achieving efficient progress in the sector.

#### 5.9. Detail complexity and dynamic complexity

When asked for measures to increase equipment reliability, a renewable energy consultant recommended to *design out complexity and failure points*. For managing complexity, the differentiation between detail (or combinatorial) and dynamic complexity as given in complex systems theory [50] is helpful:

- (i) Detail complexity is characterised by many interacting elements and by a large number of combinatorial possibilities. The respective tasks are characterised by their high level of technical or organisational complicity. Nevertheless they can be planned and handled by the application of prior knowledge, skills and tools. Groesser [51] explained that, in detail-complex situations, methods to *reduce complexity* might be useful. In the present context, the potential to reduce detail complexity is seen in applying systems engineering, standardising components and using multi-applicable technologies. When taking a look at the wider picture, a reduction of detail complexity can be achieved in the course of commercial project implementations by introducing a *competitive technology qualification routine* (as described further below).
- (ii) Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships and a need to integrate hard and soft data [52,53]. Dynamically complex systems usually contain non-linear feedbacks, time delays and accumulations. Cause and effect are subtle, and obvious interventions can produce non-obvious consequences. The process of gradually commercialising marine renewable energy comprises a high level of dynamic complexity because of the intense and decades-long interaction among many heterogeneous stakeholders. Dynamic complexity arises even in simple systems and usually cannot be reduced. In order to improve project success rates, Groesser [51] introduced *qualitative feedback modelling* as a method to analyse and handle dynamic complexity.

Research by Sterman [54] revealed that, in conventional project management, mainly aspects of detail complexity are considered. Senge [55] underlines that the real leverage in most management situations lies in understanding dynamic complexity. Also, according to his research, most established planning tools and analysis methods are designed to handle detail complexity but are not equipped to deal with dynamic complexity.

#### 5.10. Competitive technology qualification routine

The interview participants identified reliability concerns as the top-ranked non-commercial risk. On the opposite side, poor liability was mentioned as the key operational risk. The widespread

perception of high cost and unproven reliability was mentioned by the strategy manager of a public-private partnership as negatively influencing the sector. The managing director of a UK financial firm and the vice-president of a Canadian project developer emphasised that concerns regarding delays and cost-overruns mainly relate to the reliability, durability and performance of marine energy converters. A US academic named the need for longer baselines for system reliability, and an R&D vice-chair outlined that reliability is more important than efficiency. According to a Scottish government employee, the failure of devices was the most fundamental and greatest single reason for projects being delayed or costs increased. Reasons why the marine energy sector has not developed more rapidly were repeatedly identified as due to the uncertainty of device performance. The need to demonstrate equipment reliability at utility-scale was mentioned by the machinery expert of a global maritime classification society. The section manager of an Irish state agency replied to the question “*Where is research most required to accelerate the development of marine energy?*” that the reliability and integrity of devices are essential. When asked for measures by which the cost increase experienced in offshore wind can be avoided in marine energy, a project manager of a large utility recommended compromising reliability and cost. As main factors for reaching commercial generation, two senior members of classification societies stressed the prevailing uncertainty about reliability and the need to focus on it. To achieve a satisfactory technology performance record, the experts recommended to put more focus on reliability in system design and to introduce reliability modelling.

In all above interview statements, the key importance of the technological reliability was uniformly emphasised. As years will pass before full maturity is reached, the introduction of a *competitive technology qualification routine* was proposed for early commercial projects in order to achieve the required safety for investment [56,57]. The principal idea is to extend project execution by a *qualification procedure* in the course of which different manufacturers' power conversion devices are deployed and operated in real-sea conditions directly in the intended project area for a defined period of time (e.g. three months). Individual device performance is independently assessed, and the manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated. The approach represents a transparent and evidence-based selection procedure to reliably identify the most suitable technology for a specific site.

## 6. Conclusion

The principal objective of this research is to create consolidated strategic know-how to support orientating the marine energy commercialisation process. The prevailing top-ranked risks (*achieving funding* and *uncertainty in device performance*) are directly interdependent because investor confidence depends on track records of continuous device operation. In the centre of this area of conflict we find the *array-scale success*, as clearing this milestone will create confidence in the innovative generation method and consequently de-risk future investment. The identified top-level strategic principles help to efficiently prepare and manage the *array-scale success* and thus to achieve a step change in the development of marine renewables.

With reference to the initial hypothesis, the paper makes the following contribution:

*“In case major industrial competitors in the marine energy sector accept the high significance of jointly clearing the milestone array-scale success, then the motivation for applying stakeholder-wide co-ordinated strategic principles will be increased. Transparently showcasing the maturity and reliability of the technological concept will de-risk the sector and create the decisive investor confidence.”*

The presented approach of using cross-category expert interview data to elaborate unbiased system dynamics computer models is seen as a powerful method to keep track of the development and to advance co-ordinated strategy finding.

## 7. Recommendations and further research

Hull and Slowinski [58] demonstrate that co-operative relationships in high technology between large industrial conglomerates (with strong market positions) and small firms (providing innovative technology) brought innovations to market that neither firm alone could have accomplished. The



correlated term *competitive collaboration* was introduced by Hamel et al. [59] for strategic alliances that strengthen companies against outsiders (i.e. other renewables), even as they weaken each partner vis-à-vis the other. To achieve the marine energy market breakthrough and to establish a new industry with a variety of manufacturers, extraordinary concessions between *natural competitors* are required. The (temporary) joining of forces is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence. A comparable motivational state is described in [60] in the context of the market introduction of electric vehicles. The strategies applied by leading industrial conglomerates to develop the technology in a co-ordinated manner and to harmonise the technological infrastructure required for the market launch are examined.

Governing the market entry of marine renewables represents a challenging endeavour in a highly dynamic but long-term oriented business environment. Considering the present and envisaged future dimension of marine energy, co-ordinated strategic measures to substantiate the development of the sector are necessary. To ensure continuous progress on the way towards subsidy-free electricity generation, diverse problem-solving competences are necessary. The inherent detail and dynamic complexity makes it necessary to apply methods that are capable to reflect the entire commercialisation process and to systematically identify the critical success factors on a regular basis.

As the introduction of electricity generation by tidal stream and wave power is an unprecedented undertaking with significant investment and risks involved, flexible adaptation of the commercialisation process to prevailing developments and dynamic circumstances is essential. In case the maturity of the concept can be shown in the course of the *array-scale success*, then there is a prospective future for this fascinating and carbon-free electricity generation method.

## Acknowledgements

The study is part of PhD research into strategic risk management for marine energy projects at the Institute for Energy Systems, University of Edinburgh, UK. The author is grateful to Prof I. Bryden, Prof G. Harrison and H. Jeffrey for their continuous support and inspiring discussions. Thanks to all interview participants and to the anonymous reviewers for providing helpful suggestions.

## References

- [1] Scottish Government, Major Boost for Wave and Tidal Industry, <<http://news.scotland.gov.uk>>, 2013 (09/11/2013).
- [2] ScottishPower Renewables, Sound of Islay, <[www.scottishpowerrenewables.com](http://www.scottishpowerrenewables.com)>, 2013 (10/05/2013).
- [3] Agence Nationale de la Recherche, Energies marines renouvelables: Un appel à projets à venir dans le cadre de l'action, Instituts pour la Transition Énergétique, 2015. <[www.agence-nationale-recherche.fr](http://www.agence-nationale-recherche.fr)> (07/05/2015).
- [4] The Crown Estate, Wave & Tidal Programme: Future Leasing – Industry Engagement Exercise, <[www.thecrownestate.co.uk](http://www.thecrownestate.co.uk)>, 2012 (10/05/2013).
- [5] DECC, UK Renewable Energy Roadmap, Department of Energy & Climate Change, London, 2011.
- [6] The Carbon Trust, Accelerating marine energy: potential for cost reduction, London, 2011.
- [7] RenewableUK, Wave and Tidal Energy in the UK, RenewableUK, London, 2013.
- [8] R. Bucher, Strategic risk management in ocean energy, in: 10th European Wave and Tidal Energy Conference, Aalborg, Denmark, 2013.
- [9] A.K. Dixit, B.J. Nalebuff, *Thinking Strategically: The competitive Edge in Business, Politics, and Everyday Life*, W.W. Norton & Company, New York, US, 1991, ISBN 9780393310351, pp. 36–37.
- [10] A. Masini, E. Menichetti, The impact of behavioural factors in the renewable energy investment decision making process: conceptual framework and empirical findings, *Energy Policy* 40 (2012) 28–38.
- [11] S. Leete et al, Investment barriers and incentives for marine renewable energy in the UK: an analysis of investor preferences, *Energy Policy* 60 (2013) 866–875.
- [12] K. Sjøø, The Influence of Uncertainty on Venture Capital Investments in Renewable Energy Technology: An Exploratory Study, University of Oslo, 2008. <[www.duo.uio.no/handle/10852/17873](http://www.duo.uio.no/handle/10852/17873)> (06/05/2014).
- [13] L. Santos et al, Real options versus traditional methods to assess renewable energy projects, *Renewable Energy* 68 (2014) 588–594.
- [14] R. Wüstenhagen, E. Menichetti, Strategic choices for renewable energy investment: conceptual framework and opportunities for further research, *Energy Policy* 40 (2012) 1–10.
- [15] European Ocean Energy Association, Industry Vision Paper, <[www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu)>, 2013 (20/02/2014).
- [16] EMEC, Guidelines for Marine Energy Converter Certification Schemes, ISBN 978-0580650406, 2009.
- [17] N. Moghaddama, Formulating industry strategies, *Renewable Energy* 39 (2012) 299–306.
- [18] SI Ocean, Ocean Energy: State of the Art, <<http://si-ocean.eu>>, 2013 (30/05/2014).
- [19] IEA-OES, Annual Report, <[www.ocean-energy-systems.org](http://www.ocean-energy-systems.org)>, 2014 (01/05/2015).
- [20] European Commission, Ocean Energy: Action Needed to Deliver on the Potential of Ocean Energy by 2020 and Beyond, SWD, 2014, 13.

- [21] SI Ocean, Ocean Energy Technology: Gaps and Barriers, <<http://si-ocean.eu>>, 2013 (30/05/2014).
- [22] Marine Scotland, Consent granted to construct and operate the Sound of Islay demonstration tidal array electricity generating station, <[www.gov.scot](http://www.gov.scot)>, 2015 (03/05/2015).
- [23] Marine Scotland, Licence for marine renewables construction works (Inner Sound/Pentland Firth), <[www.gov.scot](http://www.gov.scot)>, 2014 (03/05/2015).
- [24] MeyGen, £51 million MeyGen financial close completed, <[www.meygen.com](http://www.meygen.com)> 2014 (03/05/2015).
- [25] GDF SUEZ, France Selects GDF SUEZ to Build a Pilot Tidal Power Farm in the Alderney Race, <[www.gdfsuez.com](http://www.gdfsuez.com)>, 2014 (02/05/2015).
- [26] MHI Vestas Offshore, Leading Edge Technology: The V164–8.0 MW® Turbine, <[www.mhivestasoffshore.com](http://www.mhivestasoffshore.com)>, 2015 (04/05/2015).
- [27] Gamesa, Ending of the Azimut Project that will Enable the Development of a 15 MW Offshore Wind Turbine in 2020, <[www.gamesa.com](http://www.gamesa.com)>, 2014 (05/05/2015).
- [28] European Commission FP6, UpWind: Integrated Wind Turbine Design, <<http://ec.europa.eu/research/energy>>, 2011 (05/05/2015).
- [29] European Commission, Ocean Energy Status Report, Joint Research Centre, Institute for Energy and Transport (2015), <http://dx.doi.org/10.2790/866387> (ISBN 978-92-79-44611-5).
- [30] IEA-OES, Annual Report, Country Report Spain, <[www.ocean-energy-systems.org](http://www.ocean-energy-systems.org)>, 2013 (06/04/2014).
- [31] M. Previsic et al., The future potential of wave power in the US, American Geophysical Union, Abstract #OS53D-08, <[www.re-vision.net](http://www.re-vision.net)>, 2012 (06/04/2014).
- [32] Global Wind Report, Annual Market Update, <[www.gwec.net](http://www.gwec.net)>, 2014 (06/05/2014).
- [33] Fraunhofer-ISE, Levelised Cost of Electricity, Renewable Energy Technologies, <[www.ise.fraunhofer.de](http://www.ise.fraunhofer.de)>, 2013 (06/04/2014).
- [34] International Renewable Energy Agency, Renewable Energy Technologies: Cost Analysis Series, [www.irena.org](http://www.irena.org), 2012 (10/04/2014).
- [35] M. Previsic, K. Shoele, Cost reduction pathways for wave energy, in: 10th European Wave and Tidal Energy Conference, Aalborg, Denmark, 2013.
- [36] IEA-OES, Ocean Energy: Review of Supporting Policies, <[www.ocean-energy-systems.org](http://www.ocean-energy-systems.org)>, 2014 (06/04/2013).
- [37] IEA, Technology Roadmap Wind Energy, <[www.iea.org/publications](http://www.iea.org/publications)>, 2013 (06/05/2014).
- [38] K.A. Karikari-Boateng et al., Reliability of tidal turbines using wind turbine experience, in: 10th European Wave and Tidal Energy Conference, Aalborg, Denmark, 2013.
- [39] R. Bucher, A literature-based review: pumped-storage and the pan-European supergrid, in: Proceedings of the Hydropower and Dams Conference Series, Bordeaux, France, 2015.
- [40] The German Offshore Wind Energy Foundation, Cost reduction potentials of offshore wind power in Germany, <[www.offshore-stiftung.de](http://www.offshore-stiftung.de)>, 2013 (18/02/2014).
- [41] J.P. Murmann, K. Frenken, Toward a systematic framework for research on dominant designs, technological innovations and industrial change, *Res. Policy* 35 (2006) 925–952.
- [42] B. Jay, H. Jeffrey, UKERC Research Atlas Topic: Marine Energy, UK Energy Research Centre, London, 2010.
- [43] S. Jacobsson, A. Bergek, Transforming the energy sector: the evolution of technological systems in renewable energy technology, *Ind. Corp. Change* 13 (5) (2004) 815–849.
- [44] H. Jeffrey et al., Accelerating the development of marine energy: exploring the prospects, benefits and challenges, *Technol. Forecast. Soc. Change* 80 (2013) 1306–1316.
- [45] M. Augustine et al., Concept convergence: a framework for improving product concepts, *Comput. Ind. Eng.* 59 (2010) 367–377.
- [46] S. Kaplan, M. Tripsas, Thinking about technology: applying a cognitive lens to technical change, *Res. Policy* 37 (5) (2008) 790–805.
- [47] D.J. Teece, Profiting from technological innovation: implications for integration, collaboration, licensing and public policy, *Res. Policy* 15 (6) (1986) 285–305.
- [48] IEA, Energy Technology Perspectives: Scenarios and Strategies to 2050, OECD/IEA, Paris, France, 2008.
- [49] E. Amanatidou, K. Guy, Interpreting foresight process impacts: steps towards the development of a framework conceptualising the dynamics of foresight systems, *Technol. Forecast. Soc. Change* 75 (2008) 539–557.
- [50] J.D. Sterman, L. Booth Sweeney, Cloudy skies: assessing public understanding of global warming, *Syst. Dyn. Rev.* 18 (2) (2002) 207–240.
- [51] S. Groesser, Projects fail because of dynamic complexity: managing complexity by qualitative feedback modelling, *Projektmanagement aktuell*, Bern University of Applied Sciences, Switzerland, 2011, 22(5), pp 18–25.
- [52] J.D. Sterman, System dynamics modelling for project management, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, USA, 1992.
- [53] K. Cooper, G. Lee, Managing the dynamics of projects and changes, in: Proceedings of the International System Dynamics Conference, Albuquerque, USA, 2009.
- [54] J.D. Sterman, Does formal system dynamics training improve people's understanding of accumulation?, *Syst. Dyn. Rev.* 26 (4) (2010) 316–334.
- [55] P. Senge, *The Fifth Discipline: The Art and Practice of the Learning Organisation*, Crown Publishing Group, New York, US, 1990 (ISBN 978-053456349).
- [56] R. Bucher, De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, in: 4th International Conference on Ocean Energy, Dublin, Ireland, 2012.
- [57] R. Bucher, I. Bryden, Overcoming the marine energy pre-profit phase, in: 2nd Asian Wave and Tidal Energy Conference, Tokyo, Japan, 2014.
- [58] F. Hull, E. Slowinski, Partnering with technology entrepreneurs, *Res. Technol. Manage.* (1990) 16–20 (November–December).
- [59] G. Hamel et al., Collaborate with your competitors and win, *Harvard Business Review* 133, 1989.
- [60] R. Bucher, H. Jeffrey, The strategic objective of competitive collaboration: managing the solid market launch of marine energy, in: 11th European Wave and Tidal Energy Conference, Nantes, France, 2015.

## **F Publications**

### **F.1 Scientific journal articles**

Bucher, R., Bryden, I.G. (2015) Governing the market entry of marine energy by symptom-adapted interventions: (i) Reduction of detail complexity; and (ii) Managing dynamically complex tasks, Journal of Energy Challenges and Mechanics, Vol. 2(2) article 4, pp56–61, ISSN 2056-9386 (originally presented at the 3<sup>rd</sup> International Symposium on Energy Challenges and Mechanics, 2015, Aberdeen, UK)



# Governing the market entry of marine energy by symptom-adapted interventions: (i) Reduction of detail complexity; and (ii) Managing dynamically complex tasks

## 通过随症状干预来进行海洋能的市场进入治理： (一) 减排细节复杂性；(二) 管理动态复杂任务

Ralf Bucher<sup>1\*</sup>, Ian Bryden<sup>2</sup>

<sup>1</sup>University of Edinburgh, Institute for Energy Systems, Mayfield Road, Edinburgh, EH9 3JL, UK

<sup>2</sup>University of the Highlands and Islands, Ness Walk, Inverness, IV3 5SQ, UK

[r.bucher@sms.ed.ac.uk](mailto:r.bucher@sms.ed.ac.uk)

Accepted for publication on 12<sup>th</sup> October 2015

**Abstract** – Governing the market entry of marine energy represents a challenging endeavour that is confronted by a series of obstacles. The harsh marine environment places considerable demands on the quality of the deployed structures and devices. Apart from technological difficulties, achieving funding is a central problem as investors show a clear preference for more mature, proven technologies. To overcome the present pre-profit phase, two different solution approaches are required: one for solving complicated technology-related or organisational tasks and another for strategic remits. In the paper, a methodology to systematically identify critical success factors is presented, and propositions to tackle detail and dynamic complexity, correlated with the commercialisation of marine energy, are made.

**Keywords** – Marine energy, market entry, detail and dynamic complexity, system dynamics modelling.

### I. INTRODUCTION

Marine energy finds itself in a decisive transition phase with operating full-scale demonstrators but an outstanding proof of the technological concept in a commercial power generation environment. Consequently, the industry goal to deliver projects of up to 50 MW by 2020 [1] requires critical evaluation, especially when considering the setbacks and delays experienced in the last years.

Managing the market entry of tidal stream and wave power represents an ambitious undertaking. In the course of a recent expert interview series, the top-ranked risks for utility-scale project implementations were identified as *uncertainty in device performance* and *achieving funding*. To ensure

continuous progress on the way towards subsidy-free electricity generation, diverse problem-solving competencies are necessary. On one side, we encounter technical difficulties that require profound engineering know-how and on the other, tasks of a more strategic nature that require qualitative assessment capabilities and advanced management concepts.

The tasks correlated with the commercialisation of marine energy can be sub-divided into questions of *detail complexity* (also referred to as *complicacy*) and *dynamic complexity*. Reducing the core problem *uncertainty in device performance* is a challenging but conventional engineering task, whereas *achieving funding* is more demanding and requires the ability to cope with many interlinked impact factors at different time scales (i.e. a classic example for dynamic complexity). In this paper, the distinctly different strategies for solving detail-complex problems and appropriately managing dynamically complex tasks are described.

### II. OBJECTIVE OF THE RESEARCH

The underlying objective of this research is to de-risk and streamline the commercialisation of power generation by tidal stream and wave power technologies. The provision of problem-specific analyses and solution approaches aims to rapidly achieve a solid and sustainable market breakthrough.

The research is oriented around the hypothesis:

*The market entry of marine energy can be de-risked by symptom-adapted interventions: (i) reduction of detail*

complexity; and (ii) managing dynamically complex tasks by qualitative feedback modelling.

The long-term focus is on establishing marine energy as a market competitive generation alternative with commercially viable projects implemented on a regular basis.

### III. RESEARCH PRINCIPLE AND METHODOLOGY

In the scientific literature on complexity research, the fundamental difference between detail and dynamic complexity is underlined [2,3]. Studies in the field of system dynamics revealed that in conventional management mainly aspects of detail complexity are considered, but that the real leverage lies in understanding dynamic complexity [4]. Senge [5] states, that most planning tools and analytical methods are not equipped to handle dynamic complexity.

In this contribution, a comprehensive approach to manage dynamic complexity correlated with the maturation and market entry process of marine energy has been chosen. The integration of a wide spectrum of perspectives in a systematic and transparent manner is a core principle applied in this research<sup>1</sup>. Different sources of knowledge are compiled to identify an optimum commercialisation strategy.

As for dynamically complex situations, a reduction of complexity can be counterproductive, qualitative feedback modelling is seen as the preferred approach [6]. In this case, expert interview information as input data and numerical modelling by system dynamics software is required.

In the course of the present research, several system dynamics models were built to fulfil the requirements of a qualitative feedback modelling process. In the initial model, the effects of dynamic complexity were considered by identifying the long-term top-level driving factors for the commercialisation of marine energy. Based on the achieved finding to focus on *showcasing commercial-scale projects/successful demonstrators*, two further system dynamics models, concentrating on aspects of detail and dynamic complexity, were developed. In order to cross-check and substantiate the results, diametrically opposite perspectives were taken to analyse the supporting and hindering impacts on the marine energy development and maturation process.

The following chronological tasks have been performed: (i) elaboration of a target-oriented questionnaire; (ii) conduction of expert interviews; (iii) compression of information by ordering terms; (iv) configuration of system dynamics computer models; (v) calculated ranking of impact factors and determination of top-level driving factors; (vi) allocation of representative core statements; and (vii) elaboration of

strategies to de-risk the technology and to govern the market entry process.

### IV. WHICH TASKS ARE COMPLICATED AND WHICH ARE DYNAMICALLY COMPLEX?

#### 4.1. LARGE-SCALE ENGINEERING & CONSTRUCTION PROJECTS

Söderlund [7] formulates that large-scale transformation projects (for which the maturation process and market launch of marine energy is an example) are characterised by involving several hundred individuals, different technologies, numerous knowledge bases, complex contractual structures and a wide range of development activities with parallel operations.

Sterman [8] demonstrates in the context of large-scale engineering and construction projects, that they consist of many *interdependent components, involve multiple feedback processes, non-linear relationships, accumulation or delay functions*, and belong, as such, to the group of *complex dynamic systems*. He emphasises that cause and effect can be subtle and *obvious interventions can produce non-obvious consequences*.

Within a research on project management, Ahern et al. [9] make the important distinction between detail-complex and dynamically complex projects. They criticise that – in line with the finding of Hayek [10] that dynamically complex tasks cannot be completely specified in advance – traditional project management privileges planning and downplays the role of learning. *Planning and problem-solving must be dealt with differently*, as summarised by Swinth [11].

#### 4.2. DETAIL COMPLEXITY (TECHNICAL COMPLICACY)

Detail complexity is characterised by *many interacting elements and a large number of combinatorial possibilities*. The respective tasks are characterised by their high level of technical or organisational complicacy. Nevertheless, they can be planned and handled by the application of prior knowledge, skills and tools. By definition, detail-complex tasks or projects can be completely specified in advance. In the context of marine energy, questions of detail complexity arise in the framework of machinery/component design (blades, rotor, nacelle, foundations, electrical system, protection, controls), in subjects related to deployment, operation and retrieval or in multi-faceted organisational tasks (legal permits, regulatory and consenting process, finance applications).

A simplified formula to describe detail complexity is to exponentiate the number of potential states of each element by the number of elements [12]. This formula is not adequate to calculate dynamic complexity.

#### 4.3. DYNAMIC COMPLEXITY

In the course of a technology convergence process, a project can change its respective characteristics. In aviation history, as exemplarily described by Ahern et al. [9], aircraft design progressed from being a complex project (when the technology was poorly understood) to a complicated project (when detailed designs are documented for production assembly). Nevertheless, as described by Snowden [13], a

<sup>1</sup> By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. Two questionnaires had to be discarded because they were incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was ultimately retained for the analysis. A total number of 2,129 individual replies had to be grouped in order to formulate higher-level correlations as the input for computer-based system dynamics analyses.



one-off project may not transition from being complex to becoming complicated until it is delivered and retrospectively comprehended in its entirety.

Dynamic complexity can arise even in simple systems with low combinatorial diversity and often shows aspects of counter-intuitive behaviour [14,15]. In the course of working on dynamically complex projects, continuous learning and reliable knowledge formation are paramount. Engwall [16] formulates this within a project management context by saying

that it is necessary to continuously create knowledge over the complete project life cycle.

In Table 1, the most typical attributes of complex dynamic systems are presented and correlated to their appearance in the course of the commercialisation of marine energy. In this context, the term *system* refers to a set of rules that governs the *market entry and commercialisation process of marine energy*.

TABLE 1, DYNAMIC COMPLEXITY IN COMMERCIALISING MARINE ENERGY [14,17 – BOTH ADAPTED]

Attribute	Root cause	Form of appearance
On-going transformations in the embedding socio-technical system [18]	Innovation and change processes occur at many levels and at different time scales.	The unstable global economic situation constitutes a dynamic environment and changing strategic priorities (nuclear power phase-out, fracking) alter policy orientation.
	—► Considering a business environment in which other renewables operate price-competitive to conventional sources and the <i>epochal transformation of the European energy system</i> , the commercialisation strategy needs to be regularly adapted to socio-political developments.	
Non-linear development and unsteady system behaviour	Non-linearity arises when (i) multiple factors interact, i.e. by complicated information pathways with many decision points; (ii) cause and effect are distant in time and space; and (iii) effect is rarely proportional to cause.	Leete et al. [19] and Wyatt [20] examined investor attitudes and found that most of them are unlikely to make any future investments in early stage device development. Venture capital investors are not closed to the industry completely, but the current level of risk and uncertainty about future revenues are discouraging them from investing.
	—► The commitment of investors is key for the commercialisation of marine energy. The present unpredictability of the costs and the length of time required to develop the technologies limit the incentive to invest and contribute to the <i>unsteady and non-linear progress in the sector</i> .	
Counter-intuitive effects and policy resistance	The complexity of the system makes it difficult to fully understand it. The attention is often drawn to symptoms rather than to underlying causes. Many seemingly obvious solutions to problems fail or worsen the situation.	The quality of challenges that the sector faces is illustrated by the decision of Siemens to sell Marine Current Turbines (a key tidal stream device developers) only two years after its acquisition. Siemens is looking to exit marine energy, saying the development of the market and the supply chain has taken longer to grow than expected [21].
	—► The recent decision of Siemens to divest of MCT is a concern for the sector [22] and reveals the <i>difficulty of forecasting the pace of development</i> towards reaching commercial generation.	
Adaptive characteristics	Evolution and learning lead to the selection and proliferation of the best concept(s) while others become extinct. Achieving a milestone alters the state of the system, thus giving rise to a new situation, which then influences the next decisions.	Marine energy represents a <i>radical innovation</i> and is driven by the need to de-risk the technology and achieve funding. Before becoming recognised as a mature power generation method, marine energy needs to prove a range of referenceable application cases. The attainment of this <i>array-scale success</i> will represent a major turning point and is expected to finally trigger industry-scale deployment.
	—► The economic success of marine energy depends on demonstrating market-readiness. By the game-changing <i>array-scale success</i> , competition between suppliers will shift to a new set of parameters of which the most important one is price [23]. <i>The development trajectory adapts</i> .	
Tightly coupled	Heterogeneous stakeholders interact intensively with one another and the natural world.	Interaction of diverge stakeholders such as governments, certifiers, investors, academia, consultancies, developers, owners, operators, manufacturers and test site operators.
	—► To successfully realise the marine energy market launch, the <i>regularly coordinated interaction of the policy, technology and finance sectors</i> is necessary.	

## V. GOVERNING THE MARKET ENTRY

In the course of this research, in total, three system dynamics computer models were developed [24]. As the first model serves as a strategic indicator, all reported positive and negative impact factors on the final target of *full commercial power generation by marine energy* were coherently grouped

and inter-correlated. The model was built one-on-one to the interview replies so that it directly reflects the experience and expectations of a wide range of stakeholders. Out of a total of 234 qualitative replies, directly defining the positive and negative impacts on the defined target, seven *representative group terms* were defined and the individual replies allocated accordingly. In a subsequent step, 16 positive (supporting/

accelerating/reinforcing) and 22 negative (hindering/delaying/countervailing) *generic terms* were formulated to correlate the individual interview replies in a systematic manner according to their number of occurrences [25,26]. The calculated results of the simulations are presented in Table 2. On the left hand side, the impact factors with negative effect and on the right hand side the ones with positive effect on

achieving market-competitive generation are represented. As the singular characteristics of government involvement and decisions are outside the range of this research, the highest ranked positive and negative top-level driving factors (*strong and long-term commitment from government* and *fluctuating or unclear political support*) were not examined in further detail.

TABLE 2, SPLIT RANKING OF TOP-LEVEL DRIVING FACTORS (POSITIVE AND NEGATIVE IMPACT FACTORS)

Negative (hindering/delaying/countervailing)	Rank	Positive (supporting/accelerating/reinforcing)	Rank
Fluctuating or unclear political support	47	Strong and long-term commitment from government	100
Lack of investor confidence	45	Showcase commercial-scale projects/demonstrators	51
Fragmented initiatives by unexperienced parties	44	Engagement industry/academia	22
Conflicts of interest (fishermen, shipping routes)	23	Cost-effective way to harvest marine energy	18
Low ability of developers to work together	17	Collaboration and consolidation between companies	15

The need to *showcase commercial-scale projects/successful demonstrators* and the identified *lack of investor confidence* are directly interdependent as investment decisions depend on track records of continuous device operation. In the centre of this area of conflict, we find the eagerly-awaited *array-scale success*, as passing this interim milestone will give confidence in the innovative sector and de-risk investments.

Subsequently, two more precisely focussed models were built to identify the top-level driving factors for achieving the *array-scale success*. In order to cross-check and substantiate the findings, diametrically opposite perspectives were taken by processing the entities of supporting and hindering impacts.

## VI. SYMPTOM-ADAPTED INTERVENTIONS TARGETING ON ROOT CAUSES

### 6.1. REDUCTION OF DETAIL COMPLEXITY

For detail-complex (or complicated tasks), the application of complexity-reducing measures is expedient [27]. Apart from technology-related questions, detail complexity also appears within stakeholder-internal business management and in tasks of organisational nature. The following measures for complexity-reduction were identified in the course of processing the multi-disciplinary expert interview data:

- (i) Standardisation and certification: Standards are one of the most important elements in the development of any industry [28]. A project developer's head of offshore operations emphasised, when asked for the most valuable experience gained by the early movers, the *experienced negative impact of missing standardisation*. One interviewee summed up the situation by saying *no standards, no results*. Considering the urgent need for consensus over standardisation, the over-engineering in oil and gas standards was addressed as being potentially hindering for the development of marine energy.
- (ii) Multi-applicable technologies and joint concepts: In the course of the interviews, a power utility ocean energy manager outlined that one of the top-priority tasks in the work of academia and research should be to concentrate on *multi-applicable technologies* and *compatible devices*

and components (e.g. moving parts, cable connectors, controls). To ensure compatible component design, effective supply chain management and leveraging logistics are required. Significant benefits are seen in *joint deployment and maintenance* programmes.

- (iii) Systems engineering: When asked about the potential to reduce the cost for utility-scale project implementations, the CEO of a wave energy firm emphasised the recognition to orientate their development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles<sup>2</sup>. In the course of the design and deployment of marine energy converters and correlated power infrastructure, *regular system functionality checks*, focussing on operation in open sea, grid-connected, multi-device arrays, are recommended. This statement correlates with the central objective in systems engineering *to consider the finally envisaged functionality already in early project stages*.
- (iv) Reliability modelling: As a key risk for reaching commercial generation, senior members of classification societies stressed *uncertainty about reliability* and emphasised the necessity to focus on it. In order to achieve a satisfactory technology reliability record, the experts recommended concentrating on reliability in system design and introducing *reliability engineering*.

### 6.2. MANAGING DYNAMIC COMPLEXITY

As a way of dealing with novel and complex tasks, Swinth [11] proposes *joint problem solving* which comprises a *common goal-orientation*, the *linkage of organisational centres* and the definition of an *overall consistent set of actions*. Within an inductive study on product innovation in continuously changing organisations (which are considered by the authors as *complex adaptive systems*), Brown and Eisenhardt [29] proclaim the importance of *extensive communication* and *design freedom* to create improvisation within current projects. They summarise that successful firms rely on *experimental products* and *strategic alliances*.

<sup>2</sup> The term *systems engineering* can be traced back to the Bell Telephone Laboratories in the 1940s. A.D. Hall presented 'A Methodology for Systems Engineering' (ISBN 0-442-03046-0) at Princeton University in 1962.

Due to on-going transformations in the embedding socio-technical system, that *encompass the co-evolution of technology and society* [18], the actual lines of strategic development of the marine energy sector need to be regularly re-adjusted. The following concepts are proposed by scholars working in the field of complex systems research:

- (i) System dynamics techniques: As an initial step in approaching the characteristics of complex systems, in the mid-1950s, Forrester [30] developed system dynamics as *a methodology and mathematical modelling technique for framing, understanding and discussing complex issues and problems*. Richardson [31] defines system dynamics as *a computer-aided approach to policy analysis and design*. Wu et al. [32] introduce system dynamics as *a manner of systematic thinking that integrates a large number of causal relationships among variables and simulates real systems through high-speed computer processing power*. Forrester [33] describes the system dynamics approach as *a tool for knowledge-based decision-making*. Yim et al. [34] explain that *system dynamics methods support decision-making and enable managers to act under dynamic and non-trivial environments*.
- (ii) Qualitative feedback modelling: With a focus on power projects, Groesser [35] argues that dynamic complexity is often the root cause for non-successful projects and introduces *qualitative feedback modelling* as a method to effectively deal with dynamic complexity. In the course of the present research, *qualitative feedback modelling* is not realised in the original form of working based on problem-specific relationship-diagrams, but by directly targeting the final goal of commercial power generation by marine energy. Feedback modelling is hereto realised at a more fundamental level by considering the marine energy commercialisation process as a complex system of which the dynamic characteristics are captured by semi-structured interviews with all active stakeholder groups [26]. The obvious analogy of this process with a closed-loop control circuit and its clearly defined (technical) terms helps to remove barriers [36–39].

As the presented concepts to deal with detail and dynamic complexity were successfully applied in similar environments, they are suitable to support de-risking the market entry of marine energy. The initial hypothesis is confirmed.

## VII. CONCLUSION

There are a series of obstacles to the market entry of marine energy. Root causes for the slow commercialisation process are concerns regarding device reliability and difficulties in attracting investment. To successfully establish marine energy as a mature power generation alternative, in-depth engineering capabilities and advanced management skills are required. In order to identify optimum measures, a particular task needs to be assessed in its entirety and corresponding strategies selected. To solve machinery-related or organisational challenges, a good standard of innovation management and experience is required. Nevertheless, such specialist tasks are,

in their principal characteristics, comparable to routinely executed R&D<sup>3</sup> activities in high-technology industry sectors.

The more comprehensive and strategically demanding tasks are to attract financing and to successfully embed the innovative generation method into the continuously changing *socio-technical environment*. To be able to adapt to such a discontinuous and non-transparent environment, systemic thinking and evolutionary steering mechanisms are required. The strategy must be flexible and re-adjustable to new trends and priorities.

The commercialisation of marine energy can be regarded as a complex dynamic system that has the capacity to change and learn from experience. There is the necessity to be mindful of the numerous time-driven impact factors and to enable learning by strengthening collaborative problem solving [40,41]. The use of cross-category expert interview data and unbiased system dynamics modelling assure the important open-integrative instead of detailed-specialist character of the research. Based on such a multi-disciplinary attempt, an all-encompassing appraisal becomes possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests.

Engwall [16] describes that *project execution is seldom a process of implementation, rather it is a journey of knowledge creation*. Reliable communication and efficient knowledge integration are seen as keys for success. The motivation for cooperative interaction to jointly de-risk the concept is given by the aim to rapidly overcome the pre-profit phase [42].

The correct strategic alignment of the sector depends on the input of all key stakeholders. The process of information gathering by *stakeholder-wide expert interviews* and the use of *system dynamics tools* to determine the currently relevant *top-level driving factors* provide a reliable foundation for governing the market entry of marine renewables.

## ACKNOWLEDGEMENT

The study is part of a PhD research into strategic risk management for marine energy projects at the Institute for Energy Systems, University of Edinburgh, UK. The first author is grateful to Prof I. Bryden, Prof G. Harrison and H. Jeffrey for their continuous support and inspiring discussions. Thanks to all interview participants and to the anonymous reviewers for providing helpful suggestions.

## REFERENCES

- [1] European Ocean Energy Association (2013) Industry Vision, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [2] Sterman, J.D. (1994) Learning in and about complex systems, *System Dynamics Review* 10(2-3), pp291–330
- [3] Schwaninger, M. (2009) Complex versus complicated: The how of coping with complexity, *Kybernetes* 38(1/2), pp83–92, DOI 10.1108/03684920910930286

<sup>3</sup> *Research and development* is a general term for activities in connection with corporate or governmental innovation.



- [4] Sterman, J.D. (2010) Does system dynamics improve people's understanding of accumulation?, *System Dynamics Review* 26(4), pp316–334
- [5] Senge, P. (1990) *The fifth discipline: The art and practice of the learning organisation*, ISBN 978-0553456349, Crown Publishing, New York
- [6] Cooper, K. & Lee, G. (2009) Managing dynamics of projects and changes, *Proceedings of the International System Dynamics Conference*, USA
- [7] Söderlund, J. (2010) Knowledge entrainment and project management, *International Journal of Project Management* 28, pp130–141
- [8] Sterman, J.D. (1992) *System dynamics modelling for project management*, MIT, Cambridge, USA
- [9] Ahern, T. & Leavy, B. (2014) Complex project management as complex problem solving, *International Journal of Project Management* 32, pp1371–1381
- [10] Hayek, F.A. (1945) The use of knowledge in society, *American Economic Review* 35(4), pp519–530
- [11] Swinth, R.L. (1971) Organizational joint problem-solving, *Management Science* 18(2), pp68–79
- [12] Schwaninger, M. (2009) *Intelligent organizations: Powerful models for systemic management*, Springer, ISBN 978-3540851615
- [13] Snowden, D. (2002) Complex acts of knowing: Paradox and descriptive self-awareness, *Journal of Knowledge Management* 6(2), pp100–111
- [14] Sterman, J.D. (2001) System dynamics modelling: Tools for learning in a complex world, *California Management Review* 43(4)
- [15] Sterman, J.D. (2002) Systems thinking and modelling for a complex world, Massachusetts Institute of Technology, Engineering systems division, esd-wp-2003-01.13-esd
- [16] Engwall, M. (1998) The project concept(s): On the unit of analysis in the study of project management, Kluwer, Boston, pp25–35
- [17] Groesser, S. (2012) Dynamische Komplexität ist die große Herausforderung für das Management, *CFO aktuell* 6(2), pp67–72
- [18] Geels, F.W. (2004) From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory, *Research Policy* 33, pp897–920
- [19] Leete, S. et al. (2013) Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences, *Energy Policy* 60, pp866–875
- [20] Wyatt, S. (2014) Financing marine energy: The role of innovation in reducing risk, 5<sup>th</sup> International Conference on Ocean Energy, Canada
- [21] Siemens (2014) Siemens says tidal sector too “niche”: MCT put on selling block, [www.tidaltoday.com](http://www.tidaltoday.com) [26/11/2014]
- [22] IEA-OES (2014) Annual Report, available from [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [accessed 20/04/2015]
- [23] Teece, D.J. (1986) Profiting from technological innovation, *Research Policy* 15, pp285–305
- [24] Bucher, R. (2013) Strategic risk management in marine energy, 10<sup>th</sup> European Wave and Tidal Energy Conference, Denmark
- [25] Bucher, R. & Bryden, I. (2014) Overcoming the marine energy pre-profit phase, 2<sup>nd</sup> Asian Wave and Tidal Energy Conference, Tokyo, Japan
- [26] Bucher, R. & Bryden, I. (2014) Strategic orientation for ocean energy market roll-out, *Journal of Energy Challenges and Mechanics* 1(2), pp1–10
- [27] Groesser, S. (2011) Projects fail because of dynamic complexity, *Projektmanagement aktuell* 22(5), pp15–25
- [28] DNV (2001) Qualification procedures for new technology, Recommended practice, Det Norske Veritas
- [29] Brown, S.L. & Eisenhardt, K.M. (1997) The art of continuous change: Linking complexity theory and time-paced evolution in shifting organizations, *Administrative Science Quarterly* 42(1), pp1–34
- [30] Forrester, J.W. (1971) Counterintuitive behaviour of social systems, *Technology Review*, Vol. 73, No. 3, pp52–68
- [31] Richardson, G.P. & Sterman, J.D. (1996) *Proceedings of the 1996 International System Dynamics Conference*, System Dynamics Society
- [32] Wu, J.-H., Huang, Y.-L. & Liu, C.-C. (2011) Effect of floating pricing policy: An application of system dynamics on oil market after liberalisation, *Energy Policy* 39, pp4235–4252
- [33] Forrester, J.W. (1961) *Industrial dynamics*, The MIT Press, Massachusetts Institute of Technology, Cambridge, USA
- [34] Yim, N.-H., Kim, S.-H., Kim, H.-W. & Kwahk, K.-Y. (2004) Knowledge based decision making on higher level strategic concerns: System dynamics approach, *Expert Systems with Applications* 27, pp143–158
- [35] Groesser, S. (2011) Measurement of dynamic complexity, *Proceedings of the 29<sup>th</sup> International System Dynamics Conference*, Washington DC, USA
- [36] Schwenke, M. & Groesser, S. (2014) *Modellbasiertes Management für dynamische Problemstellungen*, Duncker & Humblot, Berlin, pp139–150
- [37] Senge, P. & Sterman, J.D. (1992) Systems thinking and organizational learning, *European Journal of Operational Research* 59(1), pp137–150
- [38] Diehl, E. & Sterman, J.D. (1995) Effects of feedback complexity on dynamic decision-making, *Organizational Behavior and Human Decision Processes* 62(2), pp198–215
- [39] Sterman, J.D. (1989) Modelling managerial behaviour, *Organizational Behavior and Human Decision Processes* 43(3), pp301–335
- [40] Saynisch, M. (2010) Mastering complexity and changes in projects, economy, and society via PM-2, *Project Management Journal* 41(5), pp4–20
- [41] Remington, K. (2011) *Leading complex projects: Comprehend complexity*, Gower Publishing, ISBN 978-1409419051
- [42] Bucher, R. & Jeffrey, H. (2014) Creation of investor confidence: The top-level drivers for reaching maturity, 5<sup>th</sup> International Conference on Ocean Energy, Canada

## **F Publications**

### **F.1 Scientific journal articles**

Bucher, R., Bryden, I.G. (2014a) Strategic orientation for the ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge, *Journal of Energy Challenges and Mechanics*, Vol. 1(2) article 8, pp103–112, ISSN 2056-9386 (originally presented at the 1<sup>st</sup> International Symposium on Energy Challenges and Mechanics, 2014, Aberdeen, UK)



# Strategic orientation for the ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge

## 为海洋能源市场的推出作战略定位：通过跨组织专 家知识系统动力学建模进行相干技术学习

Ralf Bucher<sup>1\*</sup>, Ian Bryden<sup>2</sup>

<sup>1</sup>University of Edinburgh, Institute for Energy Systems, Mayfield Road, Edinburgh, EH9 3JL, UK

<sup>2</sup>University of the Highlands and Islands, Ness Walk, Inverness, IV3 5SQ, UK

[r.bucher@sms.ed.ac.uk](mailto:r.bucher@sms.ed.ac.uk)

Accepted for publication on 9<sup>th</sup> September 2014

**Abstract** – The development of an alternative power generation method requires, apart from long-term political support, strong commitment on the technology and financing side. Tidal stream and wave energy presently move from full-scale prototype testing to the implementation of first multi-device arrays. With the intention to gain comprehensive insight into present ocean energy activities and plannings, a diversified interview series was conducted by which 44 experts from 13 stakeholder groups provided their knowledge in the form of 2,129 individual replies. To master the amount and complexity of the multi-level information received, all interview data were systematically consolidated and formed as such the input for the configuration of representative cause-effect relationship diagrams and detailed system dynamics computer models. Based on the calculated ranking of the top-level driving factors for the ocean energy commercialisation process and the subsequent allocation of representative interview statements, balanced propositions for the strategic orientation of technology-driving stakeholders can be made.

**Keywords** – Ocean energy commercialisation, semi-structured expert interviews, system dynamics modelling, competitive collaboration, technology convergence.

### I. INTRODUCTION

The UK is currently the global leader in ocean energy, with more wave and tidal devices installed than the rest of the world combined [1]. Marine renewables form an integral part of the UK energy system transformation and are expected to make a meaningful contribution to the nation's energy mix from around 2025 [2]. After significant technological advances in the last years, the industry now moves from full-scale prototype testing to the implementation of first tidal arrays ranging from 10 to 86 MW [3-5].

To efficiently pass the present pre-profit phase and to head towards regular commercial-scale project implementations, coordinated interaction within and between the stakeholders is required. A conclusive strategy to orientate the ocean energy development process must be capable to integrate the dynamic and complex interplay between all stakeholders. To ensure efficient interaction and long-term collaboration, continuous learning and adaptation efforts are required. Systematically conditioned wide-range expert knowledge provides the best basis herefore.

### II. OBJECTIVE OF THE RESEARCH

The academic objective of the research is on the systematic transposition and refinement of expert interview statements by means of system dynamics (SD) modelling in order to de-risk and accelerate the ocean energy commercialisation process.

The research is oriented around the hypothesis:

*The right strategic orientation of the stakeholders engaged in ocean energy is crucial for efficiently reaching the goal of market-competitive electricity generation. The essential top-level drivers can be determined in a holistic and transparent manner by operating system dynamics computer models based on refined trans-organisational expert interview data.*

The hypothesis acknowledges the importance of having access to different expert knowledge bases and emphasises the need of processing multi-level data. The term “strategic” shall underline the long-term focus of 5 to 10 years and the holistic research concept by integrating the technology, policy and financing sectors. By systematically analysing the wide

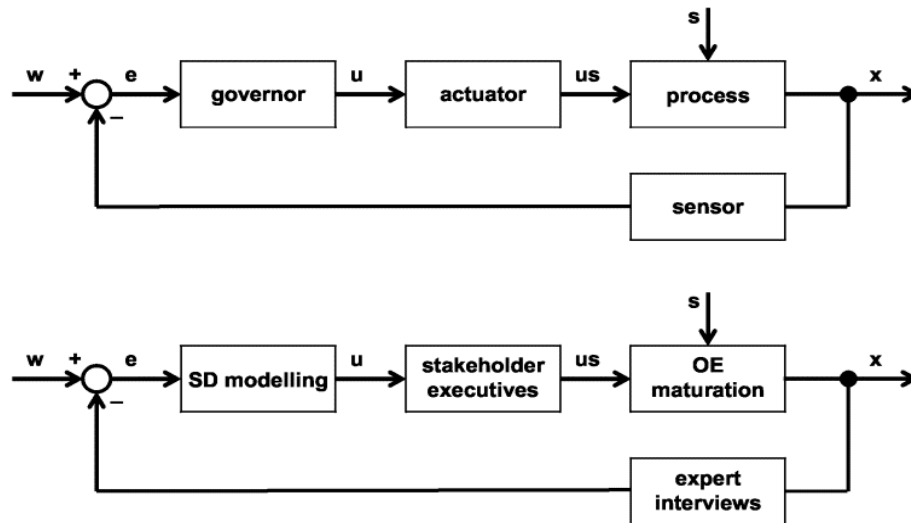


Fig. 1, Closed-loop block diagrams (top part: with ISO control theory terms / lower part: adapted to the present research context).

spectrum of stakeholder-individual strategies and concerns, potential misinterpretations and coordination deficits come to surface at time and viable superordinate strategies can be elaborated.

### III. RESEARCH PRINCIPLE AND METHODOLOGY

The basic principle applied in this research is to create new insight by compiling different sources of knowledge for the elaboration of an optimum strategy towards achieving market competitive generation. New knowledge is generally created through a process of applying multiple perspectives to the same information, as outlined in a study in the field of experimental behavioural science by Okhuysen & Eisenhardt [6]. In order to follow this principle of multiple perspectives, experts from all stakeholder groups were invited to contribute with their individual experience and know-how. Based on this multi-disciplinary attempt, an all-encompassing appraisal becomes possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests only.

The use of system dynamics modelling techniques assures the envisaged open-integrative instead of detailed-specialist character of the research. The methodology applied considers the long-term and dynamic development of the ocean energy sector by continuous information gathering and data processing oriented at feedback control principles. To master the amount and complexity of the cross-category information and to systematically identify the fundamental interview statements, all data were uniformly consolidated and formed as such the basis for the configuration of detailed cause-effect relationship diagrams<sup>1</sup>. The final system dynamics models emerged from “iterative cycles of data gathering, feedback analysis, implementation and evaluation” as described by Formentini & Romano [7] in a knowledge management context.

The research principle of data collection, information compression, system dynamics modelling and the creation of strategic propositions can be outlined by referencing to the closed-loop control model. In Fig. 1, one standard and one adapted block diagram are shown which comprise all elements defining a dynamic and complex process to be controlled – either of technical or organisational nature. The respective analogies between the terms and concepts in control theory and the present research context are shown in Table 1.

TABLE 1, ANALOGIES BETWEEN TERMS AND CONCEPTS IN CONTROL THEORY AND THE PRESENT RESEARCH CONTEXT

Control theory	Ocean energy commercialisation
Reference $w$	Full commercial power generation
Deviation $e$	Remaining development progress
Governor	System dynamics (SD) modelling
Actuating signal $u$	Calculated top-level driving factors
Actuator	Stakeholder executives
Actuating value $us$	Management decisions and actions
Process	Ocean energy (OE) maturation
Disturbance $s$	Setbacks, difficulties, risk impacts
Actual value $x$	Actual status of ocean energies
Sensor	Periodic cross-category interviews

The following chronological steps were necessary: (i) conduction of 44 expert interviews; (ii) analysis and sorting of replies; (iii) compression of information by introduction of ordering terms; (iv) configuration of system dynamics computer models; (v) calculated ranking of impact factors and definition of top-level driving factors; (vi) allocation of representative interview statements; and (vii) elaboration of recommendations for the strategic orientation of the technology, policy and financing sectors.

<sup>1</sup> System dynamics software used: Process Modeller, Consideo, Germany.

#### IV. SEMI-STRUCTURED EXPERT INTERVIEWS

For the survey, a four-page questionnaire with a total of 90 questions was elaborated out of which 48 were yes/no questions and 42 of qualitative character asking for stakeholder-specific experience or assessment. By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was ultimately retained for the analysis, corresponding to an effective return rate of 32.4 % which is more than usual for studies of this nature [8]. A total number of 2,129 individual replies had to be grouped in order to formulate higher-level correlations as basis for the computer-based SD-modelling.

Table 4 lists stakeholders that finally participated in the interviews or sent back filled-out questionnaires.

#### V. SURVEY RESULTS AND STATISTICAL FINDINGS

##### A) Virtual reference project

With the aim to harmonise and to uniformly direct the research, the interviewees were asked to give a prognosis on the development prospects of ocean energy. Utility-scale generation is expected in 2021 for tidal stream and 2024 for wave power. The average array rating is given for tidal stream at 36 MW and for wave power at 38 MW with investment cost of 102 m€ (2,900 €/kW) respectively 118 m€ (3,100 €/kW).

##### B) Interview-based ranking of selected risks

The interview participants provided estimations for risk levels focussing on the realisation of the virtual reference project (~40 MW, ~2025, ~100 m€) as follows:

- (i) Top risks: achieving funding, keeping budget, reliability.
- (ii) High risks: supply chain, time schedule, regional grid.
- (iii) Medium risks: sea use license, marine flora/fauna, conflict of interest, capability of shipyards/ports, feed-in tariff, insurance cost, extreme weather, health and safety.

Apart from financial aspects, the key risk in ocean energy is related to uncertainty in device performance or reliability.

#### VI. SYSTEM DYNAMICS MODELLING

##### A) Referenced basic model: "Full commercial power generation by marine energy"

In total 3 system dynamics models were elaborated. For the basic model explained in [9], all positive (reinforcing) and negative (countervailing) influences on the final objective of full commercial power generation by ocean energy were grouped and inter-correlated.

Out of 234 individual replies, 16 top-level driving factors essential for achieving commercial power generation were systematically identified and concentrated into 3 milestone terms:

- (i) Government support: The long-term commitment from government represents the fundament for the further progress of the sector. Early stage developments depend on coordinated funding mechanisms and fiscal measures as well as an efficient consenting process.
- (ii) Array-scale success: The 2<sup>nd</sup> ranked top-level driving factor (showcase commercial-scale projects / successful demonstrators) forms the essential element of this interim milestone that triggers the further development.
- (iii) Cost reduction: After having successfully demonstrated the array-scale success, LCOE<sup>2</sup> will decline due to serial manufacturing and technology convergence processes.

As the singular characteristics of governmental support are outside the range of this contribution, the context around achieving the interim milestone "array-scale success" was examined in detail by identifying the respective reinforcing and countervailing impact factors.

##### B) Reinforcing model: "Showcase commercial-scale projects / successful demonstrators"

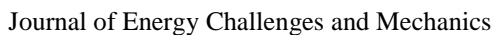
In this higher focussed model, the 2<sup>nd</sup> ranked top-level driving factor identified by the basic model of showcasing commercial-scale projects or successful demonstrators serves as new target factor. In the right hand middle area in Fig. 2 we find it being fed via 3 main nodes: (i) knowledge transfer and learning from neighbouring sectors; (ii) top-priority tasks in the work the government agencies; and (iii) having costs under control. These nodes correspond to the cornerstone elements for harnessing the potential of ocean energy presented by McSweeney as: technology, policy, financing [10].

The SD-model was configured one-on-one to the interview replies so that it directly reflects the first-hand experience and projections of all interviewed stakeholders. Based on the questionnaire, 11 representative group terms (i.e. "lessons learnt in the oil/gas industry") were pre-formulated. Out of 671 individual replies, 26 generic terms (i.e. "device operation experience") were defined. The number of replies received under a specific aspect defines the relative impact onto a node and finally on the target factor. The inter-correlation between the generic and group terms is determined by the distribution of the expert interview replies. Calculated weighting factors define the intensity of a correlation link and are displayed as normalised values. The simulation runs showed that the most important generic term (or impact factor) is "technology learning" being interconnected by strong causal links.

The elaborated cause-effect relationship diagram enables a factual representation and analysis of multi-level data.

<sup>2</sup> Levelised cost of electricity are defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.





©2014

### C) Countervailing model: “Negative impact on the development of ocean energy”

To make full use of the insight gained in the interviews, in a further system dynamics model exclusively negative, delaying or countervailing impacts (generated from 1,712 individual replies) on the development of ocean energy were considered.

### D) Simulation results and grouping of impact factors

In Fig. 3 the simulation results of the two in-depth system dynamics models described under B) and C) are shown in combined manner in the so-called “insight matrix”. On the left hand side, the impact factors with negative effect on reaching the target of full commercial power generation by ocean energy are located and on the right hand side the ones with positive effect. The y-axis indicates the impact intensity behaviour on the target over time. The greater the distance from the axes of coordinates, the more significant a factor is. As the axis scales in both examined system dynamics models are identical, the impact values can be directly compared.

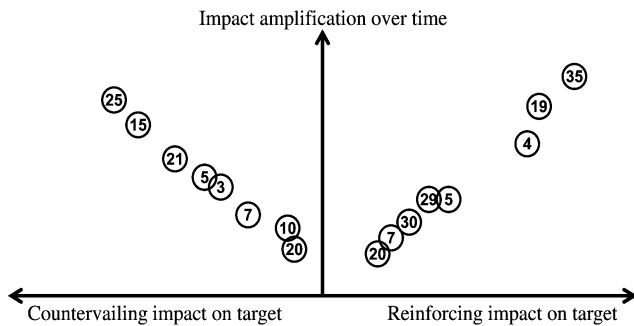


Fig. 3, Combined insight matrix showing countervailing and reinforcing impact factors on commercialising ocean energy.

Following the results of the system dynamics calculation runs on “showcase commercial-scale projects / successful demonstrators” and “negative impact on the development of ocean energy”, in Table 2 the identified countervailing (–) and reinforcing (+) impact factors are grouped and ranked according to their summarised impact levels. The item numbering (#) refers to Fig. 3.

TABLE 2, GROUPED IMPACT FACTORS (WITH IMPACT LEVELS)

–	Technology (summarised impact: 551)	+
#25	Technology learning (83+100)	#35
#15	Marine operations experience (74+86)	#19
#21	Project/risk management, EIA (61+44)	#29
#7	Device operation experience (36+27)	#7
#20	Marine technology (21)	
	Project management (19)	#20
–	Policy (summarised impact: 100)	+
#5	Consenting, leasing, licensing (51+49)	#5
–	Financing (summarised impact: 59)	+
	Reduction of CapEx and OpEx (35)	#30
#10	Funding requirement (24)	

The by far strongest impact on the objective to showcase commercial-scale projects or successful demonstrators identified by the reinforcing system dynamics model is correlated to “technology learning” (for calibration purposes defined with an impact level of 100) followed by “marine operations experience” (impact: 86). The most significant “negative impacts on the development of marine energy” are similarly related to “technology learning” (impact: 83), “marine operations experience” (impact: 74) and in third place “project/risk management and EIA (environmental impact assessment)” by an impact level of 61. The high relevance of business development (#3 & #4) as the intermediary element between technology, policy and financing is underlined by a significant impact level of 123 (46+77).

### E) Compilation of corresponding interview statements

In Table 3 the most relevant recommendations and strategy options for the sector-specific orientation are given. They are based on the calculated prioritisation by the system dynamics simulation software and correlated expert statements.

## VII. STRATEGIC ORIENTATION (TECHNOLOGY)

### A) Systems engineering approach

When asking for significant potential to get the cost for utility-scale project implementations down, the CEO of an Irish wave energy converter manufacturer emphasised the clear recognition to orientate the development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. The vice president of a multi-national engineering conglomerate underlined in similar manner the importance to prove that systems work reliably and to focus on end user requirements. This statement correlates with the central objective in systems engineering as to consider the finally envisaged functionality already in early project stages. An important element in the design and implementation process of complex technological systems is to perform regular system functionality checks. Finally, the ocean energy converters have to operate on the long term in open sea grid-connected multi-device arrays.

### B) Multi-applicable technologies and joint concepts

According to the opinion of a utility’s ocean energy project manager, one of the top-priority tasks in the work of academia & research should be to concentrate on multi-applicable technologies and standardised devices and components (e.g. moving parts, cable connector systems, control interfaces). The benefit by working along a robust engineering plan targeting on serial production and large-scale manufacturing was underlined. To finally ensure identical component design and delivery, effective supply chain management and leveraging logistics is required. Referencing to offshore wind, in [11] it is pointed out that joint installation and maintenance concepts for adjacent wind farm locations significantly increased installation and operating efficiency.

### C) Standardisation (look at volume manufacturing)

The reply of a project developer’s head of offshore when asking for the most valuable experience gained by the early

TABLE 3, STRATEGIC ORIENTATION FOR THE TECHNOLOGY, POLICY AND FINANCING SECTORS

<p><b>Technology</b> with reference to interview replies under “technology learning, marine operations experience, project/risk management and EIA, device operation experience, marine technology, project management”</p> <ul style="list-style-type: none"> <li>▪ Adopt systems engineering principles inspired by the space-/aircraft industry</li> <li>▪ Consider that extreme engineering is required with a focus on survivability and reliability</li> <li>▪ Reduce the number of technological concepts (technology convergence)</li> <li>▪ Develop multi-applicable technologies (standardisation of components) and joint concepts</li> <li>▪ Design for installation and maintenance purposes</li> <li>▪ Minimise the lack of collaboration and improve knowledge sharing</li> <li>▪ Gain offshore deployment experience with full-scale devices</li> <li>▪ Move from device testing towards array-scale activities under open sea conditions</li> <li>▪ Integrate risk management into project management</li> <li>▪ Consider the need to restructure and commit to the supply chain</li> </ul>
<p><b>Policy</b> with reference to interview replies under “consenting, leasing, licensing”</p> <ul style="list-style-type: none"> <li>▪ Facilitate consenting, leasing, licensing (i.e. with a single point of handling the process)</li> <li>▪ Promote cross-interaction between renewables</li> <li>▪ Stimulate appropriate risk sharing between the stakeholders</li> <li>▪ Encourage initiatives to bring in expertise from offshore oil &amp; gas marine operations</li> <li>▪ Focus on availability of qualified personnel and heavy marine services</li> <li>▪ Underline the importance of knowledge sharing (central bottleneck)</li> <li>▪ Improve collaboration and alignment between industry, utilities, academia, device manufacturers and project developers</li> <li>▪ Support grid-connected test facilities and pilot zones</li> <li>▪ Support strategies for grid operation with significant wave and tidal power in-feed</li> <li>▪ Simplify access to the international (out of Europe) market</li> </ul>
<p><b>Financing</b> with reference to interview replies under “reduction of CapEx and OpEx, funding requirement”</p> <ul style="list-style-type: none"> <li>▪ Recognise that pilot projects with availability records provide confidence in the performance of the core technologies</li> <li>▪ Support technologies with declared synergies towards off-shore wind</li> <li>▪ Consider the likelihood of early-stage failures and the failing in unexpected parts of project</li> <li>▪ Keep in mind that realism is required when it comes to the (global) scale of the industry</li> <li>▪ Focus on cost of energy and not on CapEx</li> <li>▪ Consider that the cost of energy production is dependent on the capacity deployed</li> <li>▪ Evaluate the insurability of projects</li> <li>▪ Recognise differences to offshore oil &amp; gas with regard to design, manufacturing and logistics</li> <li>▪ Realise the advantage of working with the already existing companies in the market</li> <li>▪ Encourage contract structuring and contract standardisation as in onshore wind</li> </ul>

movers, was the “experienced negative impact by missing standardisation”. Considering the urgent need for consensus over standardisation, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). A marine renewables engineer employed with an energy consulting firm identified “consensus over standardisation” as a target that appeared more difficult to reach in the last years than originally planned. One interviewee summed up the situation as “no standards, no results”. The overall importance of standardisation in ocean energy was emphasised by several interviewees when highly appreciating the published results by the standardisation group within one of the top three certification companies. The date of publishing new technical standards and the level of detail need to be carefully discussed with manufacturing companies to avoid early-stage limitations on non-published but promising R&D projects and unnecessary cost increase. A senior contracts

expert of an international UK law firm mentioned the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms). Contract splitting (e.g. in turbines, fundament, transformer station, inner-park cabling) as in offshore wind was recommended.

#### D) Technology convergence

According to a senior principal surveyor of a global offshore classification society, a top-priority task in their work is towards technology consolidation. A utility’s representative underlined the potential to get the cost for commercial-scale project implementations down by the positive impact of technology convergence. Augustine et al. [12] concentrate in their research on technology convergence and concept evaluation processes in industrial product development. They emphasise that rather than selecting the better among available



alternatives, the progression towards better solutions by combining the strengths of all available concepts is a more robust approach for concept improvement. It is expected that the presently high number of technological concepts in ocean energy will be reduced in the course of competitive project implementations. Considering the dynamic development in wind power, it is noteworthy that since the beginning in the 1980ies until today the rotor diameter has increased from 15 to 124 m and the nameplate rating from 50 to 5,000 kW [13]. The next development step in offshore wind is expected to be the introduction of 7 or even 10 MW turbines [14].

#### *E) Knowledge sharing and knowledge transfer*

The limited knowledge sharing in industry is seen by the strategy manager of a public-private partnership and the head of energy of UK's innovation agency as a main reason why the ocean energy sector has not developed more rapidly. A senior policy officer of the Scottish government emphasised the need to transfer lessons learnt in the offshore wind industry to ocean energy in order to avoid duplication of time and effort. According to the vice-chair of the largest private R&D group in Spain, the transfer of knowledge from other sectors (under consideration of the specific aspects of ocean energy) is identified as a top-priority task in the commercialisation process. The project manager for the implementation of the world's first commercial breakwater wave power plant outlined that the need to improve the sharing of bad (!) experience and testing data is key. According to his commissioning experience, sometimes unspectacular and cheap items created unexpected difficulties. To support progress, his position is to inform (as far as possible) about such complications at conferences, to explain why things went wrong and to display the finally implemented solution.

#### *F) Maximising collaboration and minimising competition*

In line with the findings on limited sharing of knowledge, a lack of collaboration of the industry was reported. Apart from improving cooperation, a strengthening of interaction between the device manufacturers and the engineering consultancies companies was called for. The head of policy of a major UK developer emphasised the expectable benefits by enhanced collaboration between individual project developers. With regard to academia, he mentioned the need to intensify international collaboration. The artificial competition with on-/offshore wind was criticised by an Irish ocean energy development manager as negatively influencing an uninterrupted progress. A chance to improve cross-interaction between the renewable energies is seen in identifying prospective synergy effects by inter-coupling different kinds of carbon-free generation methods. The interviewed head of development of a wave energy device manufacturer – which recently entered into a research and development collaboration with a major offshore wind developer – underlined the attractiveness of exploring the prospects by combining wave and wind power. Seeking synergies with other manufacturers considering the use of similar technology is seen as a natural process. The experienced increasing involvement and interaction with major industrials in the ocean energy sector is seen as positive and will help to restructure the supply chain.

#### *G) Offshore deployment experience*

With the aim to demonstrate the viability of electricity generation by ocean energy, it is required to provide transparency to investors and to focus on “bringing some 10 MWs in the water” as the programme director of a leading UK centre of sustainable energy expertise and pioneering project delivery outlined. Especially the importance to design for installation and maintenance purposes was emphasised by the representative of a wave energy converter manufacturer. As lessons learnt in the offshore oil & gas industry to be transferred to ocean energy, a senior manager at a Canadian utility mentioned their focus on reliability and survivability.

#### *H) Competitive collaboration and inter-firm alliances*

Ocean energy needs to assert its position in the competitive renewable energy market. Regular commercial projects will finally be realised under established international procurement principles for which a number of similarly competent industrial bidders is required. In case natural competitors accept the high significance of jointly achieving the identified intermediate milestone “array-scale success”, the motivation for inter-firm alliances will rise. Exemplary strategic alliances on how to develop new products and to penetrate new markets can serve as references. The benefits by inter-firm co-operations need to be individually examined in the course of risk/reward assessments. In a recently published paper from the European Ocean Energy Association [15], clear reference was given towards Airbus which was classified as a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments. Amanatidou & Guy [16] emphasise the increasing importance of knowledge-based industries and focus on aligning existing perceptions by maximising collaboration and minimising competition. As described by [17] cooperative relationships between firms in high technology can bring to market new innovations that neither firm alone could have accomplished. Especially for firms which are not part of the group of ocean energy front-runners, new inter-firm collaborations offer potential to prepare for global competition. The term “competitive collaboration” was introduced by [18] for strategic alliances that strengthen companies against outsiders (i.e. other renewables) even as they weaken each partner vis-à-vis the other.

#### *I) Strategic risk management*

Conventional risk management procedures are mainly tailored for stakeholder-specific duties or project-related functions. When opening risk management towards accompanying an energy system transformation project – for which the development and grid-integration of ocean energy is a good example – the usually considered time frame and the grade of complexity increase. Frigo & Anderson [19] explain that strategic risk management encompasses the interdisciplinary intersection of strategic planning, risk management and strategy execution. The development manager of a wave energy converter firm explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He generally stressed the requirement to share risk by

collaboration and to integrate risk management into project management. Modern strategy-based and life-cycle oriented management incorporates real-time management of risks. Risk sharing shall be contractually optimised to identify the most appropriate risk owners.

#### J) Adjusting the “installed capacity / capacity factor”-ratio

The principal scientist of UK wave power developer underlined that the cost of energy production is dependent on the capacity deployed. In Bucher [20] this relationship was examined for an envisaged 600 MW tidal array in Korea. Based on a full lunar cycle 3D tidal regime model, detailed statements on optimising the “installed capacity / capacity factor”-ratio and consequently limiting the financial risk could be made. The possibility to select a preferred ratio of capital investment to profit widens the circle of potential investors and helps to effectively de-risk early-stage project initiatives.

#### K) Detail complexity and dynamic complexity

When asking for measures to increase equipment reliability, a renewable energy consultant recommended to “design out complexity/failure points”. For managing complexity, the differentiation between detail (or combinatorial) and dynamic complexity as in the complex systems theory [21] is helpful:

- (i) Detail complexity is characterised by many elements and a large number of combinatorial possibilities. Groesser [22] explained that in detail-complex situations methods to reduce complexity might be useful. In the present context potential to reduce detail complexity is seen in applying systems engineering, standardising components and using multi-applicable technologies. When taking a look at the wider picture, a reduction of detail complexity can be achieved in commercial project implementations in the course of a “competitive technology qualification routine” (as described further below). The long-term best-performing device or system would be identified in a transparent process.
- (ii) Dynamically complex systems contain non-linear feedback, time delays and accumulations. Cause and effect are subtle and obvious interventions can produce non-obvious consequences. It might arise even in simple systems and can usually not be reduced but managed. Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships and the need to integrate hard and soft data [23,24]. The process of commercialising ocean energy comprises high dynamic complexity because of the continuously varying interaction between heterogeneous stakeholders over a decade’s long period of time. In order to improve project success rates, Groesser [22] recommends qualitative feedback modelling as a method to analyse and manage dynamic complexity. In the ocean energy context, potential to handle the high dynamic complexity is seen in the “interview/modelling/action”-approach in Fig. 1.

Research revealed that in conventional project management mainly aspects of detail complexity are considered [25]. Senge [26] underlines that the real leverage in most management

situations lies in understanding dynamic complexity. According to his research, most established planning tools and analysis methods are designed to handle detail complexity but are not equipped to deal with dynamic complexity.

#### L) Competitive technology qualification routine

The interview participants identified reliability concerns as the top-ranked non-commercial risk and on the opposite side poor liability was mentioned as key operational risk. The widespread perception of high cost and unproven reliability was mentioned by the strategy manager of a public-private partnership as negatively influencing the sector. A US academic named the need for longer baselines for systems reliability and an R&D vice-chair emphasised that (currently) reliability is more important than efficiency. The managing director of a UK financial firm and the vice president of a Canadian project developer emphasised that concerns for delays and cost-overruns mainly relate to reliability, durability and performance of ocean energy converters. According to a Scottish government employee, the failure of devices was the fundamental and greatest single reason for projects being delayed or cost increase. Reasons why the ocean energy sector has not developed more rapidly were repeatedly identified in the uncertainty of device performance and reliability. The requirement to demonstrate equipment reliability at utility-scale devices was formulated by the machinery manager of a global maritime classification society. The division head of an Irish state agency replied to the question on where research is most required to accelerate the development of marine energy that reliability and integrity of devices are essential.

When asking for measures by which the experienced cost increase in offshore wind can be avoided in ocean energy, a marine energies project manager of a large utility recommended to compromise cost and reliability. As main factors for reaching commercial generation, two senior members of classification societies stressed uncertainty about reliability and the need to focus on it. To achieve a satisfactory technology reliability record, experts recommended to put more focus on reliability in system design and to introduce reliability modelling.

In all above listed interview statements the key importance of technology reliability was uniformly emphasised. As years will pass until full technology maturity will be reached, Bucher [27] proposed for early commercial project implementations a competitive technology qualification routine to achieve the required safety for investment. The principal idea is to extend the execution of utility-scale projects by a qualification procedure in the course of which different manufacturers' power conversion devices are deployed and operated in real-sea conditions in the final project area for a defined period of time. The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated.

The competitive technology qualification routine represents a transparent and evidence-based selection procedure to identify most suitable technology for a site. In a carefully selected project environment, the approach might apply.

## VIII. CONCLUSIONS AND RECOMMENDATIONS

The principal objective of this research is to create strategic knowledge to orientate the ocean energy (technology) learning processes towards reaching commercial power generation. Considering the dimension and potential of ocean energy, elaborate measures to coordinate the development of the sector are necessary. The inherent high dynamic complexity of such an undertaking makes it necessary to apply tools and methods that are capable to reflect the entire process and to identify top-level driving factors in a holistic but systematic manner.

In order to rapidly overcome the present pre-profit phase, the clearing of the interim milestone “array-scale success” represents a key target, which will pave the way towards the envisaged market roll-out. To safely identify the decisive technical-organisational principles to be applied, the unbiased inclusion of trans-organisational expert knowledge is required. The use of cross-category interview data to configure system dynamics computer models is seen as the adequate basis to comprehensively assess the prevailing situation and to provide effective recommendations for the stakeholders’ medium- and long-term strategy planning and adjustment.

Referencing to the initial hypothesis, the paper makes the following contribution:

*The top-ranked risks for utility-scale ocean energy projects (achieving funding, uncertainty in device performance) are directly intercorrelated as investor confidence mainly depends on track records of continuous device operation. Clearing the identified interim milestone “array-scale success” will create confidence and de-risk investments. Intensified technology learning is seen as determinant for the development of the sector. It comprises strategic principles such as applying systems engineering, strengthening standardisation and minimising competition by competitive collaboration. System dynamics computer modelling provides the tools to master the complexity of multi-level interview data and to impartially identify top-level drivers. Representative expert interview statements can be directly allocated based on the calculated ranking of priority and subsequently be analysed in detail.*

With the presented principles, specific experience can be integrated for the benefit of a coordinated way towards commercially viable electricity generation by ocean energy.

The paper shall conclude with a convincing statement given by one interviewee:

*“Generally, if device developers can successfully operate their demonstration devices at a high level of availability for an extended period of time (at least 3 years) then most of the other desirable outcomes, such as investment, takeovers by large companies, grid upgrades and so on, would follow automatically”.*

## ACKNOWLEDGEMENT

The study is part of a PhD research into strategic risk management for marine energy projects at the Institute for Energy Systems, University of Edinburgh, UK. The author is

grateful to the interviews participants and Prof Bryden for his continuous support and inspiring discussions. Thanks to the anonymous reviewers for providing helpful suggestions.

TABLE 4, LIST OF PARTICIPATING STAKEHOLDERS

<b>Government (associations) &amp; trade organisation:</b> The Scottish Government (UK), Marine Scotland (UK), Energy Technologies Institute (UK), Carbon Trust (UK), Department of Energy and Climate Change (UK), The Crown Estate (UK), Scottish Natural Heritage (UK), Centre for Environment, Fisheries & Aquaculture Science (UK), RenewableUK (UK), Technology Strategy Board (Ireland).
<b>Certifying authorities:</b> Det Norske Veritas (UK), Lloyd’s Register (UK).
<b>Investors &amp; lenders:</b> Green Giraffe (UK).
<b>Law firm:</b> Eversheds International (UK).
<b>Academia &amp; research:</b> University of Washington (USA), University of Edinburgh (UK), National Taiwan Ocean University (Taiwan), Irish Marine Institute (Ireland).
<b>Engineering consultancies:</b> Natural Power (UK), Xodus Group (UK), Tecnia Research & Innovation (Spain), South West Renewable Energy Agency (UK), Royal Haskoning (UK).
<b>Project developers:</b> Emera (Canada), EDF (France), Electricity Supply Board (Ireland), Iberdrola (Spain).
<b>Owners &amp; operators:</b> ScottishPower Renewables (UK), Ente Vasco de la Energía (Spain).
<b>Transmission system operator:</b> Scottish and Southern Energy Renewables (UK).
<b>Device manufacturers:</b> Marine Current Turbines (UK), Pelamis Wave Power (UK), Wavebob (Ireland), Siemens (Germany), Wave Star (Denmark), Ocean Renewable Power Company (USA).
<b>Offshore contractors:</b> 6 contacted (no feedback).
<b>Test site operators:</b> European Marine Energy Centre (UK), Fundy Ocean Research Centre for Energy (Canada), National Renewable Energy Centre (UK), Minas Basin Pulp & Power (Canada), France Energies Marines (France).
<b>NGO:</b> Greenpeace (UK).
<b>Offshore wind industry:</b> Dong Energy Power (UK).
<b>Oil &amp; gas industry:</b> 4 contacted (no feedback).

## REFERENCES

- [1] RenewableUK (2013) Wave & tidal energy, [www.renewableuk.com](http://www.renewableuk.com) [13/02/2013]
- [2] Low Carbon Innovation Co-ordination Group (2012) Marine energy summary report: Technology innovation needs assessment, UK
- [3] Scottish Government (2013) Major boost for wave and tidal industry, <http://news.scotland.gov.uk> [09/11/2013]
- [4] ScottishPower Renewables (2013) Sound of Islay, [www.scottishpowerrenewables.com](http://www.scottishpowerrenewables.com) [10/05/2013]



- [5] MCT (2013) Skerries Tidal Array secures consent, [www.marineturbines.com](http://www.marineturbines.com) [10/05/2013]
- [6] Okhuysen, G.A. & Eisenhardt, K.M. (2002) Integrating knowledge in groups: How formal interventions enable flexibility, *Organisation Science* 13 (4), pp370–386
- [7] Formentini, M. & Romano, P. (2011) Using value analysis to support knowledge transfer in the multi-project setting, *International Journal of Production Economics* 131, pp545–560
- [8] Masini, A. & Menichetti, E. (2012) The impact of behavioural factors in the renewable energy investment decision making process, *Energy Policy* 40, pp28–38
- [9] Bucher, R. (2013) Strategic risk management in ocean energy: A system dynamics approach to the evaluation of 40+ expert interviews, *Proceedings of the 10th European Wave and Tidal Energy Conference*, Aalborg, Denmark
- [10] McSweeney, J. (2012) Ocean energy: Harnessing the potential, *Proceedings of the 4th International Conference on Ocean Energy*, Dublin, Ireland
- [11] Cost Reduction Potentials of Offshore Wind Power in Germany, *The German Offshore Wind Energy Foundation*, [www.offshore-stiftung.de](http://www.offshore-stiftung.de) [18/02/2014]
- [12] Augustine, M. et al. (2010) Concept convergence: A framework for improving product concepts, *Computers & Industrial Engineering* 59, pp367–377
- [13] Oceans of Opportunity, Harnessing Europe's largest domestic energy resource, A report by the European Wind Energy Association, [www.ewea.org](http://www.ewea.org) [26/07/2010]
- [14] Jensen, D. & Könemann, D. (2010) *Alpha Ventus operation offshore*, ISBN: 978-3870734794
- [15] Industry vision paper 2013, *European Ocean Energy Association*, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [16] Amanatidou, E. & Guy, K. (2008) Interpreting foresight process impacts: Steps towards the development of a framework conceptualising the dynamics of foresight systems, *Technological Forecasting & Social Change* 75, pp539–557
- [17] Hull, F. & Slowinski, E. (1990) Partnering with technology entrepreneurs, *Research Technology Management* (November-December), pp16–20
- [18] Hamel, G. et al. (1989) Collaborate with your competitors and win, *Harvard Business Review* 133
- [19] Frigo, M.L. & Anderson, R.J. (2009) Strategic risk assessment: A first step for improving risk management and governance, *Strategic Finance*, pp25–33
- [20] Bucher, R., Couch, S.J. (2013) Adjusting the financial risk of tidal current projects by optimising the “installed capacity / capacity factor”-ratio already during the feasibility stage, *International Journal of Marine Energy*, <http://dx.doi.org/10.1016/j.ijome.2013.05.008>
- [21] Sterman, J.D. & Booth Sweeney, L. (2002) Cloudy skies: Assessing public understanding of global warming, *System Dynamics Review* 18(2), pp207–240
- [22] Groesser, S. (2011) Projekte scheitern wegen dynamischer Komplexität: Qualitative Feedbackmodellierung zur Komplexitätsbewältigung, *Bern University of Applied Sciences*, [www.bfh.ch](http://www.bfh.ch) [10/03/2013]
- [23] Sterman, J.D. (1992) System dynamics modelling for project management, *Sloan School of Management, Massachusetts Institute of Technology, Cambridge*
- [24] Cooper, K. & Lee, G. (2009) Managing the dynamics of projects and changes, *Proceedings of the International System Dynamics Conference*, Albuquerque
- [25] Sterman, J.D. (2010) Does formal system dynamics training improve people's understanding of accumulation? *System Dynamics Review* 26(4), pp316–334
- [26] Senge, P. (1990) *The fifth discipline: The art and practice of the learning organization*, ISBN 978-0553456349, Crown Publishing Group, New York
- [27] Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, *Proceedings of the 4<sup>th</sup> International Conference on Ocean Energy*, Dublin, Ireland

## **F PUBLICATIONS**

### **F.2 Peer review conference poster**

Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, Proceedings of the 4<sup>th</sup> International Conference on Ocean Energy, Dublin, Ireland



## ABSTRACT

The principal idea outlined in this poster (and the corresponding paper) is to **extend** the execution of **utility-scale marine energy projects** by a **competitive technology qualification routine** during which different manufacturers' power conversion devices are installed and operated in **real-sea conditions** in the project area for a defined period of time. The **individual device performance** is assessed and the manufacturer of the **best-ranked system** is awarded the principal contract.

## FOCUS OF THE RESEARCH

Today's **conventional power projects** are realised within an **established framework of proven project implementation concepts and mature technology**. The equipment procurement is realised by **international competitive bidding (ICB)** within a **balanced system of standards and guidelines**.

Marine energy finds itself in a **transition phase** from implementing first arrays - enabled by **direct agreements between utilities and manufacturers** [1-6] - towards becoming a mature electricity generation method. In contrast to offshore wind, the technology development does not benefit by extension from reliable onshore devices. As the reliability proof of marine energy equipment has to be provided under harsh marine conditions, fundamentally different **technology qualification concepts** and deployment strategies are required.

The following aspects represent decisive success factors for investors in the course of the planning and implementation of reliable, cost-effective and environmentally sound marine energy farms:

- How can the safe identification of the best-suitable tidal energy converters (TECs) or wave energy converters (WECs) be ensured for a specific site?
- Which measures simplify the integration and operation of multi-megawatt intermittent generation in an existing high-voltage transmission system?

## DE-RISKING MARINE ENERGY INVESTMENTS

In the IEA report 'Scenarios & Strategies to 2050' [7] it is outlined that most new technologies have higher costs than the incumbents and that it is only through **technology learning as a result of marketplace deployment** that these costs are reduced and the product adapted to market needs.

Technology learning in a competitive environment has been successfully proven at:

### a. The Alpha Ventus Wind Farm

Twelve 5 MW turbines installed 45 km off the shore in 30 m water depth. The experience gained by **different designs and the combination of concepts** provided valuable information regarding efficiency and system reliability [8].



Fig. 1: Alpha Ventus: a combination of technologies

- 2 turbine types
  - 5M (REpower)
  - M5000 (Areva)
- 2 foundation types
  - tripod
  - jacket
- Application of various construction methods

### b. The Ansari X-Prize

A US\$ 10,000,000 prize was offered for the first non-government organisation to launch a re-usable manned spacecraft into space twice within two weeks aiming to **spur the development of low-cost spaceflight** [9].



Fig. 2: Commercial spaceflight prototype 'SpaceShipOne'

- 26 teams
  - from volunteer hobbyists to
  - large corporate-backed operations
- Re-usable private vehicles capable of flying to 100 km altitude

### c. The DARPA Urban Challenge

Autonomous vehicles had to **prove their capability of driving in traffic**, performing complex manoeuvres such as merging, passing, parking and negotiating intersections. The winning team was awarded US\$ 2,000,000 [10].



Fig. 3: Robots performing complex driving manoeuvres

- 39 teams invited to a rigorous eight-day vehicle testing
- Robots navigated in city streets together with manned and unmanned vehicles
- After a run-time of over 4 hours the first robot crossed the finish line

As different as above examples are with regard to technological aspects, their daily relevance and the amount of investment, they have one aspect in common: in all cases a widespread **research and market spectrum** became accessible leading to the identification of the best-suitable concept(s).

Transferred to a marine energy context, the technology qualification can be realised as follows:

### Reliability proof of TECs/WECs

To assess the suitability of the participating devices at different locations within the project area, one TEC/WEC will be deployed in each representative sector by each manufacturer A to Z. By this approach the **complete range of prevailing marine conditions** is covered.

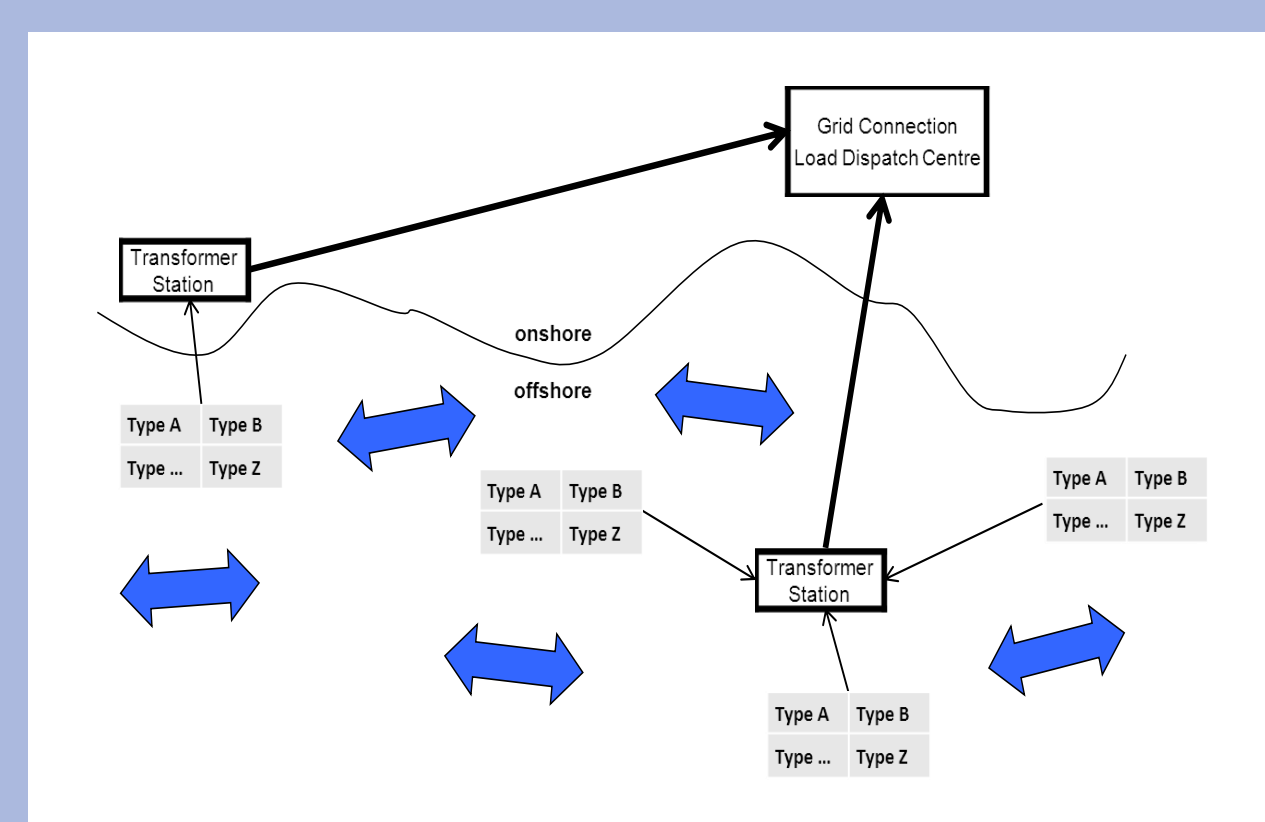


Fig. 4: Spatial arrangement for technology qualification

- Test operation for defined period of time (~3 months)
- Best-ranked system selected according to pre-defined evaluation criteria
- Compensation of non-successful competitors

By integrating device manufacturing companies into the early stages of commercial projects the **industrial research** becomes highly focussed. Creating an **appropriate framework with market-driven mechanisms** accelerates the naturally slow technology evolution processes and supports the **emergence of dominant designs**.

## COMPETITIVE TECHNOLOGY QUALIFICATION ROUTINE

In conventional power projects usually proven technology with extensive reliability records is used. As several years will pass until TECs/WECs have reached full technical maturity and due to the fact that **marine energy projects are characterised by individual requirements and constraints**, for an interim period the required **safety for investment** can be achieved by a **project-inherent competitive technology qualification routine**.

By an optimised project phasing, the **construction-, installation- and operation-experience** gained during **high-risk project phases** can be considered before awarding the principal contract.

### Conventional power project phasing

A standardised project phasing applied in conventional power projects according to FIDIC [11] is shown in Fig. 5.

It can be seen that **high-risk areas are mainly located towards the end of the project implementation**, which is considered as unfavourable. Valuable feedback is not available at time to effectively reduce the correlated technical and organisational risks.

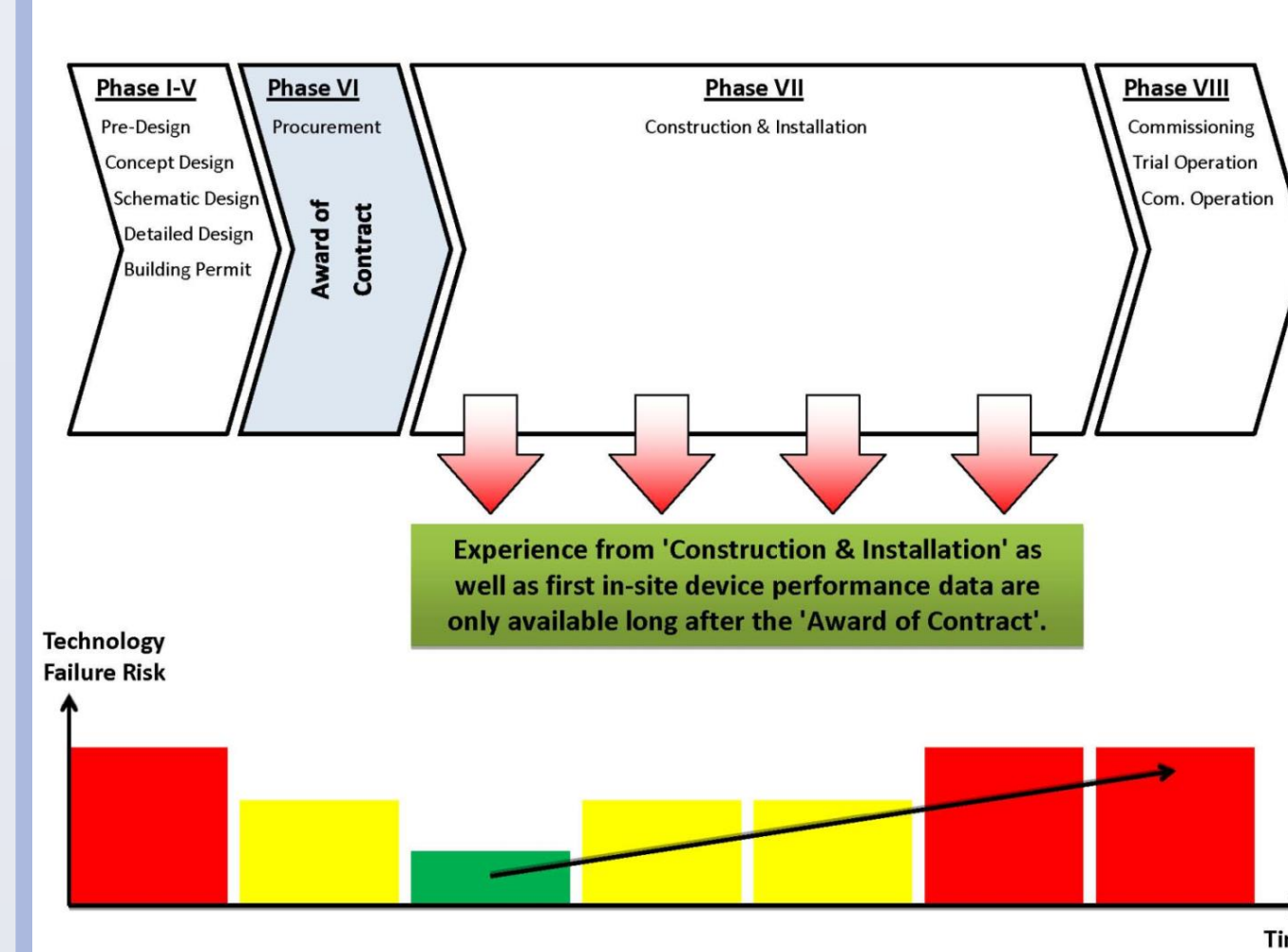


Fig. 5: Conventional power project phasing: high-risk phases at the end of the project

### Optimised marine energy project phasing

Contrary to conventional power projects and in line with the requirements of the competitive technology qualification routine, in Fig. 6 the **decisive project phase VII is extended** and further sub-divided.

Relevant **performance results are available before awarding the principal contract** and can therefore consequently be considered to the benefit of the project.

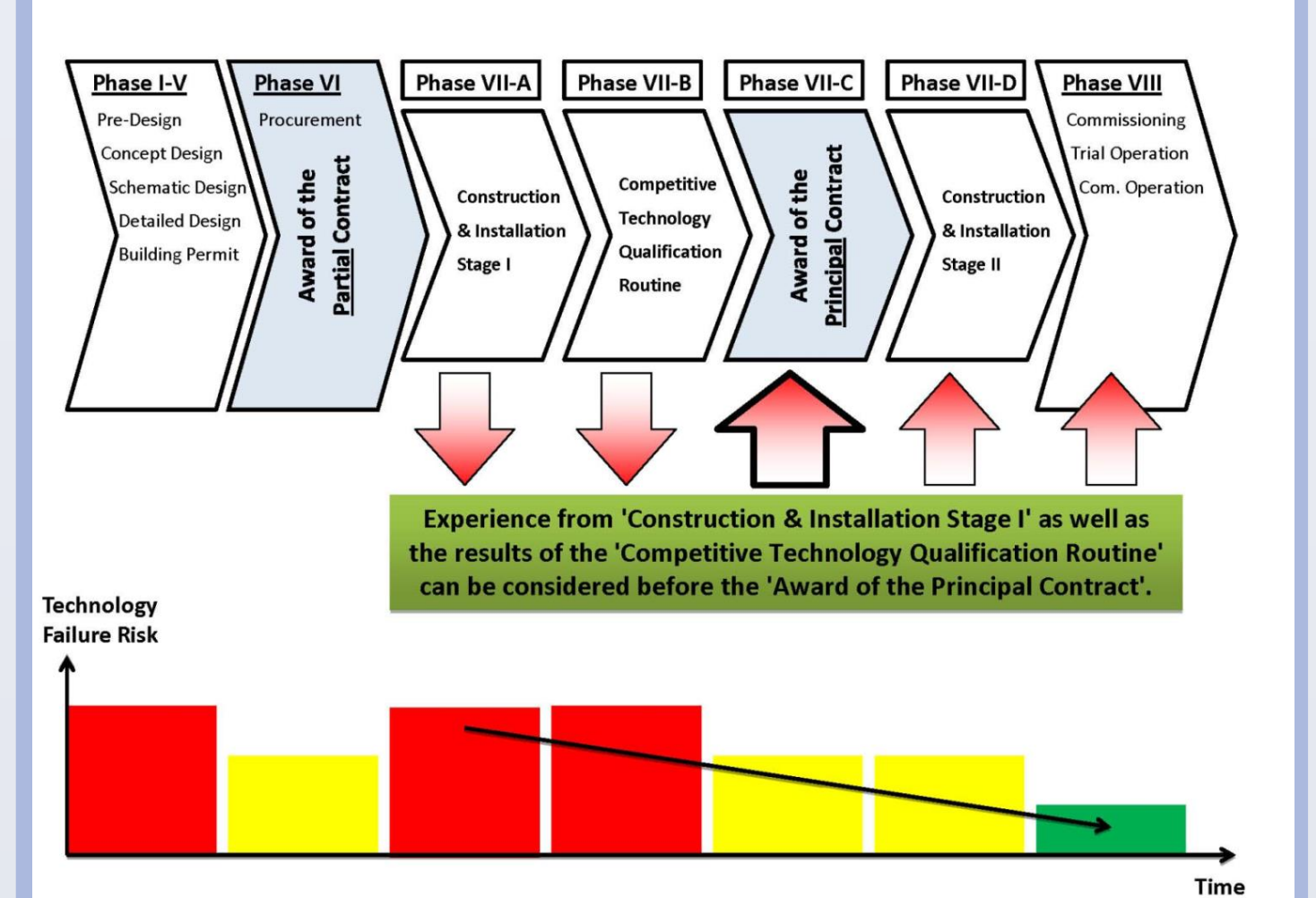


Fig. 6: Optimised marine energy project phasing: high-risk phases advanced to earlier project stages

Note: The estimated project-phase-related 'technology failure risk'-levels are displayed qualitatively in 3 categories: low risk (green), medium risk (yellow) and high risk (red).

In Fig. 6 it is shown that by the backflow of information gained during phases VII-A and VII-B the **'technology failure risk'-levels steadily decline** towards the final project implementation stages.

The top objective is to increase the **predictability of the economic performance** of commercial marine energy projects and to further encourage the implementation of utility-scale projects.

## CONCLUSIONS

Effective mechanisms to **accelerate utility-scale tidal current and wave power project implementations** require the close **examination and coordination of the interests of the project developer and the equipment manufacturers**. Considering the application of **pioneering technology** in the complex marine environment, an appropriate project set-up and contract structuring is necessary.

Extending marine energy projects by a **competitive technology qualification routine** gives the industry the chance to **bring in their expertise in early stages** and to further adapt their portfolios to market requirements. The described technology qualification routine represents a **transparent and evidence-based decision-making process** in order to reliably identify the **most suitable machinery equipment for a specific marine site**. The concept supports the maturation of all participating manufacturers' product range by identifying the **best-performing devices in real marine conditions and under a long-term perspective**.

Advancing and de-risking the critical stages of commercial-scale project implementations stabilises the confidence in the marine energy sector and significantly improves the **investment security**.

Referencing to the two introductory questions and considering the **presented ideas**, it can be concluded that by a **competitive technology qualification routine**,

- the **reliable identification of the best-suitable TECs/WECs** is substantially supported; and
- the **integration of multi-megawatt intermittent generation** in existing transmission systems is simplified by the **commissioning of a temporary array with a limited number of TECs/WECs**.

In [12] it is emphasised that rather than only selecting the best among alternatives, the **progression towards better solutions** can be found in **combining the strengths of all available solutions** within given constraints. This is considered as a robust approach for the **concept improvement**.

**Combining the experience** by testing different make and type TECs/WECs during the competitive technology qualification routine will trigger the development of innovative solutions and prepare the way towards the implementation of larger commercial marine energy parks.

## ACKNOWLEDGEMENTS

The author is grateful to all participants in the expert interviews on '**strategic risk management for tidal current and wave power projects**' conducted since June 2012 and Prof Bryden at the IES for his continuous support and the inspiring discussions.

In case you are interested in **participating in the scientific survey**, please contact the author by e-mail or phone: +49-157-72943159. Each participant receives a **copy of the summary report**.

## REFERENCES

- [1] www.scottishpowerrenewables.com, accessed on 17.07.2012
- [2] www.pelamiswave.com, accessed on 11.05.2012
- [3] Voith Hydro and RWE Innogy install marine tidal current turbine off the Scottish coast, www.rwe.com and www.voith.com, accessed on 19.11.2010
- [4] www.vattenfall.com, accessed on 19.06.2012
- [5] www.openhydro.com, accessed on 10.07.2012
- [6] www.oceanpowertechnologies.com, accessed on 12.07.2012
- [7] International Energy Agency (IEA), Energy technology perspectives, Scenarios & Strategies to 2050, OECD/IEA Paris, France, 2008
- [8] Alpha Ventus - A pioneering project, International Sustainable Energy Review, Issue 2, 2010
- [9] Composite spacecraft wins X-prize, Reinforced Plastics, Vol. 48, Issue 10, November 2004, Page 5
- [10] Defense Advanced Research Projects Agency (DARPA) Urban Challenge 2007, www.darpa.mil/grandchallenge, accessed on 26.10.2010
- [11] FIDIC Estonia Seminar, Policy and Contract Trends, Peter Boswell, General Manager, FIDIC (Fédération Internationale des Ingénieurs-Conseils), 10/2010
- [12] Augustine, M. et al.: Concept convergence process: A framework for improving product concepts, Computers & Industrial Engineering 59 (2010) 367-377



## **F Publications**

### **F.3 Peer review conference papers**

Bucher, R., Jeffrey, H. (2015) The strategic objective of competitive collaboration: Managing the solid market launch of marine energy, Proceedings of the 11<sup>th</sup> European Wave Energy Conference, ISSN 2309-1983, Nantes, France

# The strategic objective of competitive collaboration: Managing the solid market launch of marine energy

Ralf Bucher<sup>1</sup>, Henry Jeffrey<sup>2</sup>

University of Edinburgh, Institute for Energy Systems, Kings Buildings, Mayfield Road, Edinburgh EH9 3JL, United Kingdom

<sup>1</sup>R.Bucher@sms.ed.ac.uk, <sup>2</sup>Henry.Jeffrey@ed.ac.uk

**Abstract**— Electricity generation by tidal stream or wave power technologies represents a radical innovation and is confronted by significant technological and financial challenges. Considering a business environment in which other renewables operate price-competitive to conventional sources, the market entry of marine energy is seen as a one-off chance. To overcome the present pre-profit phase, achieving the milestone “array-scale success” is key for the successful development of the sector. The long-term goal of de-risking the technology and establishing a new market requires to join forces and to stimulate cooperative behaviour between the competitors. As power projects are usually realised under the terms of international competitive bidding, a number of equally capable manufacturing firms is either way required to ensure realistic pricing and to avoid single bidder dependency. In this contribution, we explore how competitive collaboration between manufacturers can positively influence the success rate of achieving a solid market launch. The focus of the research is on establishing marine energy as a generation alternative with commercially viable projects implemented on a regular basis.

**Keywords**— Market launch, technology development, competitive collaboration, system dynamics modelling

## I. INTRODUCTION

Marine energy finds itself in a decisive transition phase with full-scale technology demonstrators but an outstanding proof of the concept in a commercial project environment. The industry goal to deliver projects of up to 50 MW by 2020 [1] requires critical evaluation when considering the setbacks and delays experienced in the last years. The quality of challenges that the sector faces is illustrated, for example, by the decision of Siemens to sell Marine Current Turbines as one of the key tidal stream technology developers, because of the inability to attract match-funding for a 10 MW tidal energy farm in Wales. Siemens informed that the development of the market and the supply chain have taken longer to grow than expected [2].

In the course of the present research, numerous experts provided estimations for risk levels focusing on the realisation of tidal stream or wave power reference projects (capacity ~40 MW, implementation ~2025, investment ~120 m€). The top-ranked risks were identified as “achieving funding” and “uncertainty in device performance”. Both risk complexes are directly interdependent as investor confidence depends on track records of continuous device operation [3]. To improve the funding situation and to increase the system reliability, key milestones and strategic principles are identified based on cross-category interview data and multi-perspective system

dynamics modelling. Before becoming recognised as a mature and competitive electricity generation method, marine energy needs to prove a range of referencable application cases. The attainment of the confidence-building “array-scale success” will represent a major turning point for the global marine energy business and is expected to create the required investor confidence to finally trigger large-scale deployment [4].

As marine energy systems represent a “radical innovation” as per the term used by Geels [5], the shift to a new “socio-technical system” (i.e. the interplay of production, diffusion and use of technology) includes the creation of a new market. In most cases, radical novelties can only break through after growing in a protected environment and under the support of subsequent strategic investments. At the example of the market introduction of electric cars, these circumstances are explained based on decisions by major industrials like BMW, Daimler, Toyota and Tesla.

Considering the present and envisaged future dimension of marine energy, coordinated strategic measures to substantiate the development of the sector are necessary. The inherent high complexity of such an undertaking makes it necessary to apply methods that are capable to reflect the entire process and to identify top-level driving factors on a regular basis. The presented approach of using comprehensive expert interview data to configure system dynamics (SD) computer models is seen as a promising tool to maintain the overview and to reliably support strategy finding.

## II. OBJECTIVE OF THE RESEARCH

The underlying objective of this research is to de-risk the commercialisation of electricity generation by tidal stream and wave power technologies. The provision of supportive arguments for intensifying strategic inter-firm cooperation aims on achieving a solid and multi-company-based market breakthrough.

The research is oriented around the hypothesis:

*Competitive collaboration between device manufacturers improves the success rate of the marine energy market launch.*

The long-term focus is on establishing marine energy as a market competitive generation alternative with commercially viable projects implemented on a regular basis.

## III. RESEARCH PRINCIPLE AND METHODOLOGY

The integration of a wide spectrum of perspectives in a systematic and transparent manner is a core principle applied



in this research. Different sources of knowledge are compiled to identify an optimum commercialisation strategy for efficiently achieving market-competitive energy production. The use of system dynamics modelling techniques assures an open-integrative instead of detailed-specialist character of the research. Based on this multi-disciplinary attempt, an all-encompassing appraisal becomes possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests.

Experts from all active stakeholder groups were invited to contribute with their individual experience and knowledge. For the survey, a questionnaire with a total of 90 questions was elaborated out of which 48 were yes/no questions and 42 of qualitative character asking for stakeholder-specific assessments. By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was ultimately retained for the analysis, corresponding to an effective return rate of 32.4% which is more than usual for studies of this nature [6]. A total number of 2,129 individual replies (received during June 2012 and April 2013) had to be grouped in order to formulate higher-level correlations as the input for computer-based SD analyses.

To master the amount and complexity of the multi-facetted interview information and to reliably identify fundamental statements, all data were uniformly consolidated and formed as such the basis for the configuration of detailed cause-effect relationship diagrams. The methodology applied enables a dynamic interplay between knowledge creation, knowledge compression and targeted knowledge diffusion.

Appendix A lists stakeholders that finally participated in the interviews or sent back filled-out questionnaires.

#### IV. PROTECTED SPACES FOR INNOVATION

Carlsson et al. [7] identified in the course of innovation studies that “market-linked technological systems are not static but need to evolve continuously to be able to survive” and that it is necessary “to understand the dynamics that make a system change over time”. Due to regular transformations in embedding socio-technical systems which “encompass the co-evolution of technology and society” [5], the actual lines of technology development need to be regularly re-adjusted.

Alkemade et al. [8] explain from an innovation studies perspective, that “new technology often has difficulty to compete with embedded technologies” and outline that “most inventions are relatively inefficient at the date when they are first recognised as constituting a new innovation”. Negro et al. [9] hereto formulate more specific that “renewable energy technologies have a hard time to break through in the energy market dominated by fossil fuel technologies that reap the benefits from economies of scale, long periods of technological learning and socio-institutional embedding”. If the gap between new and established technology is very large and if there is a “paucity of nursing” or missing “bridging

segments” that allow for a gradual generation of increasing returns, a new technology may never have the chance to rectify the initial disadvantages [10].

Scholars in evolutionary economics have highlighted the importance of “niches” that act as “incubation rooms” for radical novelties, shielding them from mainstream market selection. Such protected environments enable to “overcome conventional organisational (i.e. socio-technical) inertia” (e.g. [11], [12]). Bergek et al. [13] confirm that technology development can best take place within specially created “learning spaces”, that allow a new technology to develop a technical trajectory (for reaching maturity or even a dominant design). Erickson and Maitland [14] describe that “nursing markets” need to be created to support the technology breakthrough taking advantage of “windows of opportunity” that drive adjustments in the socio-technical regime [15].

In marine energy, since several years we can see significant development taking place within “protected incubation rooms” in the form of marine energy test facilities, pilot projects or by subsidised feed-in tariffs. As such artificially created learning environments can be maintained only for a limited time, a directed and concise strategy for the market launch in one single attempt is crucial. It should be in the elementary interest of the manufacturing firms to make best use of the present period of “trial and error” by an extraordinary level of sharing knowledge with competitors and by establishing effective cooperative interaction [16].

#### V. FROM EXPERT INTERVIEW DATA TO STRATEGIC DRIVERS

##### A. Link Between Interview Data and Relationship Diagrams

In the course of this research, three system dynamics computer models have been developed. For the basic model, explained in [4], all positive (reinforcing) and negative (countervailing) influences on the pre-defined target of “full commercial power generation by marine energy” were grouped and inter-correlated. The model was built one-on-one to the interview replies so that it reflects the experience and expectation of all interviewed stakeholders. Out of a total of 234 individual replies, 16 top-level driving factors, essential for achieving commercial power generation, were identified and concentrated into three milestone terms:

- (i) Government support: The “strong and long-term commitment from government” represents the basis for the further progress of the still embryonic sector.
- (ii) Array-scale success: The 2<sup>nd</sup> ranked top-level driving factor (“showcase commercial-scale projects/successful demonstrators”) forms the essential element of this interim milestone that triggers large-scale deployment.
- (iii) Cost reduction: After having demonstrated the “array-scale success” in the course of near-commercial projects, the levelised cost of electricity will decline due to serial manufacturing effects and technology convergence.

As the singular characteristics of government regulations are outside the range of this research, focus is put on the interim milestone “array-scale success”. The effective

In the second and higher focussed model (Fig. 1), the identified top-level driving factor “showcase commercial-

examined in full detail by analysing 671 corresponding expert interview replies.

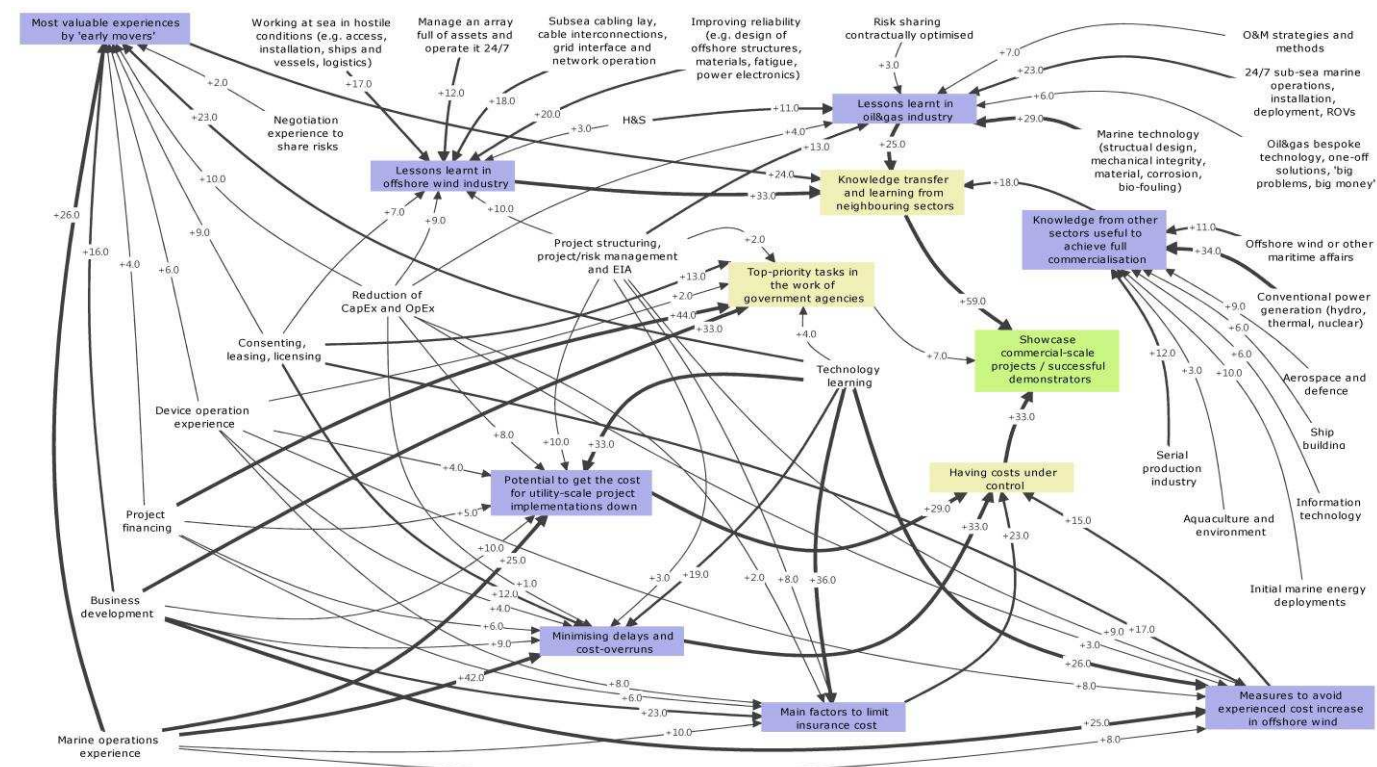


Fig. 1. System dynamics model: “Showcase commercial-scale projects/successful demonstrators”

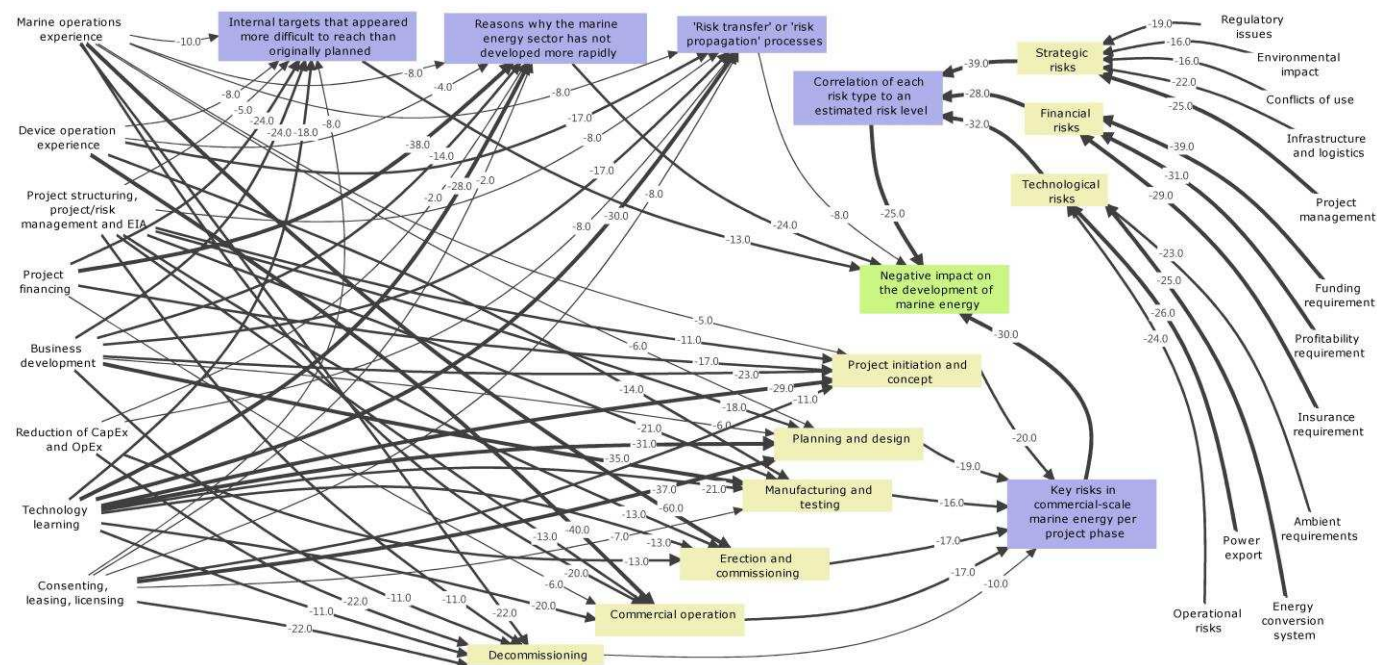


Fig. 2. System dynamics model: “Negative impact on the development of marine energy”

To make full use of the insight gained in the course of the interviewing process, in a third SD model (Fig. 2), exclusively the negative impact factors (generated from 1,712 replies)

hindering, delaying or countervailing the development of marine energy were examined. The target factor was set as “negative impact on the development of marine energy”.

In summary, the central cluster of impact factors acting on the interim milestone “array-scale success” is check-tested by processing the entity of negative impacts. By taking this diametrically opposite perspective, the research findings are substantiated and balanced.

In Fig. 3, the simulation results of the two in-depth SD models are shown in combined manner. On the x-axis, the intensity of the impact factors acting on the development of marine energy is represented. The y-axis indicates the impact behaviour on the target factor over time. The greater the distance from the axes of coordinates, the more significant a factor is. As the axis scales in both examined SD models are identical, the impact levels can be directly compared.

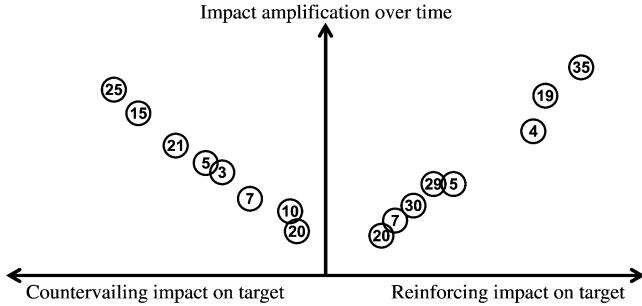


Fig. 3. Compilation of impact factors acting on the development of the sector

Following the results of the system dynamics calculation runs, in Table 1, the most important countervailing (–) and reinforcing (+) impact factors acting on the target of market competitive electricity generation are shown according to their effective strength. The item numbering (#) refers to Fig. 3.

TABLE I  
GENERIC TERMS (WITH NORMALISED IMPACT FACTOR LEVELS)

–	<b>Technology Sector</b>	+
83	Technology learning (#25 & #35)	100
74	Marine operations experience (#15 & #19)	86
61	Project/risk management and EIA (#21 & #29)	44
36	Device operation experience (#7 & #7)	27
	Marine technology (#20)	21
19	Project management (#20)	
–	<b>Policy Sector</b>	+
51	Consenting, leasing, licensing (#5 & #5)	49
–	<b>Financing Sector</b>	+
	Reduction of CapEx and OpEx (#30)	35
24	Funding requirement (#10)	

The by far strongest impact on showcasing commercial-scale projects, identified by the reinforcing SD model, is correlated to “technology learning” (for calibration purposes defined with an impact level of 100), followed by “marine operations experience” (impact: 86). The most significant “negative impacts on the development of marine energy” are similarly related to “technology learning” (impact: 83), “marine operations experience” (impact: 74) and “project/risk management and EIA (environmental impact assessment)” by an impact level of 61. The high relevance of “business development” (#3 & #4) as the key intermediary element between the technology, policy and financing sectors is underlined by a significant impact level of 123 (46+77).

## B. Compilation of Representative Interview Statements

In Table 2, the correlated statements and strategy options for the technology sector received during the expert interviews, are presented. They form the basis for the “strategic drivers for a solid market launch” described in chapter IX.

TABLE II  
STRATEGIC ORIENTATION FOR THE TECHNOLOGY SECTOR

*Representative Interview Statements Received under the Generic Terms in Table 1: Technology Learning, Marine Operations Experience, Project/Risk Management and EIA, Device Operation Experience, Marine Technology and Project Management:*

- Adopt systems engineering inspired by space-/aircraft industry
- Extreme engineering with focus on survivability and reliability
- Reduce number of concepts (technology convergence)
- Develop multi-applicable technologies and joint concepts
- Standardisation of components
- Design for installation and maintenance purposes
- Minimise lack of collaboration and improve knowledge sharing
- Gain offshore deployment experience with full-scale devices
- Move from device testing to open sea array-scale activities
- Design out complexity and failure points
- Integrate risk management into project management
- Risk sharing contractually optimised

## VI. ARGUMENTS FOR COMPETITIVE COLLABORATION

### A. Terminology

Competitive collaboration is a form of strategic alliance between two or more independent firms that “interact to pursue a set of agreed upon goals to contribute and to share benefits on a continuing basis in one or more key strategic areas” [17]. Companies enter such alliances with clear strategic objectives while they guard themselves against transferring competitive advantageous to ambitious partners [18]. Competitive collaboration can strengthen the partner companies against outsiders even as it weakens one partner vis-à-vis the other. As a partner’s objectives might affect the own success, employees at all levels must be aware what corporate information is off limits to be transferred. Hull and Slowinski [19] demonstrate that cooperative relationships in high technology between large industrial conglomerates (with strong market positions) and small firms (providing innovative technology) brought innovations to market that neither firm alone could have accomplished. Larsson et al. [20] outline that the relationship is reinforced by the degree to which the competitive objectives diverge between the partners. It is considered as advantageous when the size and market power are modest compared to the industry leaders. Especially for firms, which are not part of the group of front-runners, competitive collaboration offers significant potential for growth. Benefits are seen in achieving technological advancement, getting market access and gaining insight into the partner’s business practices and strategies. Stiles [21] analysed global collaborative partnerships and reports that 50% are deemed as failures, not realising their full potential due to the required high level of expertise and management skills. The potential benefit by inter-firm cooperation needs to be examined in the course of in-depth risk/reward assessments.

### B. Comparable Motivational State in the Automotive Industry

89.7 million cars were manufactured worldwide in 2014 out of which 0.23% were equipped with electric drive. Due to the dominance of fossil-fuel vehicles and the massive global oil infrastructure, the market introduction of electric cars has the character of a radical or even disruptive innovation. As marine energy finds itself in a comparable starting position, the strategies applied by industrial conglomerates in the car sector to prepare the market launch are worth having a closer look on:

a) BMW and Daimler announced a cooperation with the strategic goal of achieving the wholesale market rollout of electric cars by working on a common infrastructure for inductive battery charging [22].

b) Ford, Nissan and Daimler have signed a hydrogen fuel cell development agreement in an effort to bring affordable vehicles to market by 2017. The companies, which have so far been working on the technology separately, plan to jointly develop a common electric vehicles system. As such, a clear signal is sent to suppliers, policy-makers and industry to encourage the further development of hydrogen refuelling stations and other infrastructure necessary to allow the vehicles to go to the mass market [23].

c) Toyota decided to give away fuel cell patents to encourage other automakers to enter their concept and to boost as such the industry [24].

d) The electric car manufacturer Tesla is treating its patents as open source and informs that “it’s not the other companies that are our competition, but the combustion engine itself”. Tesla has set the goal of populating the world with battery stations to fuel the future of electric cars. An interesting standpoint of the company is that “patents are meant to slow competition but they also slow innovation” [25].

Håkansson [26] concludes that collaborative relationships are of strategic importance to companies but underlines that considerable investment is required to establish and maintain cooperation until the partners can derive benefit from it. He describes that collaborative relationships generally “evolve organically” and that “the starting point is often an already established relationship where mutual trust has developed”. To his opinion, it can be problematic to plan joint activities to any greater degree, especially “if the planning model is overly simple or rigid, it may well do more harm than good”.

### C. Opportunities in the Marine Energy Sector

Marine energy needs to assert its position in the highly competitive energy market. Utility-scale electricity generation by marine energy is expected by the interviewed experts in average to be mature in the year 2021 for tidal stream and in 2024 for wave power. The envisaged market introduction can be seen as a unique opportunity taking into account the continuously difficult funding situation and the incalculable consequences of negative press in the course of implementing first commercial arrays. To make full use of this one-off chance, intense and trustful collaboration is required to provide reliable solutions. It must be avoided that marine energy goes to market without fully developed components or a questionable long-term system performance.

Negro et al. [9] criticise in a renewable energy context that “entrepreneurs compete in a very early stage with each other, instead of forming coalitions and alliances in order to be more influential with respect to changing regulations, obtaining resources and creating a niche market”. According to the underlying survey, cooperative strategies are selected only after encountering difficulties, disappointments and lack of support from government entrepreneurs. In [27] and [28] it is described in the context of technological innovation systems<sup>1</sup>, that most “actors seem to be unaware of the fact that tough competition in very early phases of development reduced the chances of survival for most emergent technologies”. At the example of biomass digestion and gasification, it is explained that emerging technologies go through a 10-30 years trajectory of development, diffusion and implementation, which requires long-term policy goals and to stick to those policies. Collaboration between stakeholders focusing on knowledge development and knowledge diffusion is seen as a key system function.

As there is at present more market confidence in tidal stream than in wave power, the form and intensity of cooperation might be different between the technologies [29]. In tidal stream, cooperation might focus apart from project management aspects on non-turbine parts (foundations and moorings, balance of plant), the requirements on surrounding infrastructure (cable connector systems, grid and control interfaces, port facilities), aspects of operation (device/array interaction, offshore inventions) and resource characterisation. In wave power, the technology convergence process is fully ongoing and a consistent assessment framework is required by which less credible technologies can be screened out.

Reliability is an important factor of success for emerging technologies. In marine energy, this proof remains a major challenge as most devices to date have been in the water only for relatively short periods. Jay and Jeffrey [30] describe that in the marine energy sector there are a number of technologies and components, which offer opportunities for shared learning but underline that support and transfer of generic knowledge is limited by commercial competition. In case industrial competitors accept the high significance of jointly achieving a long-term-oriented market success, then the motivation for entering into strategic alliances will rise [31].

### VII. MARKET CREATING BY TRUSTFUL JOINT EFFORTS

Leete et al. [32] examined investor attitudes and behaviours towards wave and tidal technologies. Of the investors engaged in venture capital funding, all revealed that they were unlikely to make any future investment in early-stage device development. It is reported that private investors are not closed to the industry completely, but the current level of risk and uncertainty are discouraging them from investing. Venture capitalists abstain from investing because of high capital requirements and the uncertainty of costs, respective future revenues. Track-records of continuous device operation

---

<sup>1</sup> Technological innovation systems consist of networks of firms, R&D infrastructure, educational institutions and policy-making bodies that interact in a specific technology area to generate, diffuse, and utilise technology.

of at least six months are seen as pre-requisites for further investments. At the current stage of development, strategic investment in partnership with industry investors is seen as key for moving towards commercialisation.

Talke [33] underlines the importance of elaborate market entry operations especially for products with high grades of novelty. As concluded by Alkemade et al. [8], governments play a crucial role in creating niche markets, because they hold the power to change legislation and can articulate demand for a new technology by acting as early users or by formulating policy targets. Within the marine energy context, Corsatea [34] identified that positive interactions between technology developers and policy-makers empower market formation.

As years will pass until full technology maturity is reached, Bucher [35] proposed a comprehensive type of “incubation room” referred to as a “competitive technology qualification routine”. The principal idea is to complement the execution of large projects by a qualification process in the course of which different manufacturers’ power conversion devices are deployed and operated under real-sea conditions in the final project area for a defined period of time. The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the main supply contract. Non-successful competitors are compensated. Competitive technology qualification routines would facilitate a transparent and evidence-based selection process to identify the most suitable technology for a specific site.

## VIII. COMPARABLE RESEARCH AND RECENT LITERATURE

An approach to improve the interaction between policy (i.e. the European Commission) and technology stakeholders (i.e. the wave and tidal industry) was started in June 2012 by the Strategic Initiative for Ocean Energy<sup>2</sup> (e.g. [36], [37]). The aim of the EU-supported project was to elaborate industry-led strategies that provide tangible recommendations to facilitate the development and large-scale deployment of wave and tidal energy technologies (Table 3). The consortium held various workshops and webinars reaching 455 participants, whilst communicating with a network of 800+ contacts.

TABLE III  
INDUSTRY-LED STRATEGIES IDENTIFIED BY SI OCEAN

<i>Addressing Technology Development, by ...</i>
<ul style="list-style-type: none"> <li>▪ initiating new RDI&amp;D<sup>3</sup> programmes,</li> <li>▪ validating the reliability of devices,</li> <li>▪ creating standards and guidelines for performance evaluation,</li> <li>▪ fostering industrial co-operation and knowledge exchange.</li> </ul>
<i>Facilitating Deployment and Risk Reduction, by ...</i>
<ul style="list-style-type: none"> <li>▪ creating a network of European test and demonstration facilities,</li> <li>▪ collaborating for installation, operations and maintenance,</li> <li>▪ EU cross-industry co-operation for serial manufacturing,</li> <li>▪ cross-sector platforms for marine energy grid integration.</li> </ul>

<sup>2</sup> SI Ocean was a two year project, funded by the European Commission's Intelligent Energy Europe programme. The main goal was to deliver a common strategy for ensuring maximal wave and tidal energy installed capacity by 2020, paving the way for exponential market growth.

<sup>3</sup> Research, development, innovation and demonstration.

Magagna and Uihlein [38] describe that marine energy faces four main bottlenecks: technology development, finance and markets, environmental and administrative issues as well as grid availability. The slow technological progress combined with difficulties in attracting funds and financing for array demonstration projects are identified as limiting investor confidence in the sector.

Bonar et al. [39] argue that a greater public acceptance of renewable energy developments can be achieved by open communication, education, information sharing and improved public engagement practices. It is described that a more strategic and collaborative research effort between developers, academia and the public sector will lead to improvements in environmental monitoring standards and in best practices for device and array design.

MacGillivray et al. [40] highlight the sensitivity of the marine energy development to the capital cost of first devices and the rate of cost reduction with deployment. It is emphasised that continued and sustained growth of the sector is dependent on reaching early cost-competitiveness with other forms or renewable energy indicating the urgent need for demonstrating the long-term technology viability.

Leete et al. [32] say that track records and reliability are paramount as confidence in the capability of the technology is fundamental for achieving market acceptance.

In all cited references, possible advantages by intensified collaboration and trans-organisational interaction are indicated. Nevertheless, stakeholder-wide coordinated concepts and strategies to clear the singular hurdle of getting market acceptance are rarely presented. The required efforts for putting corresponding measures into practice can be justified by the long-term benefits after the market breakthrough. The current systemic problems need to be targeted in a coherent manner with highest level coordinated strategic targets.

## IX. STRATEGIC DRIVERS FOR A SOLID MARKET LAUNCH

### A. Systems Engineering

When asking for significant potential to get the cost for utility-scale project implementation down, the CEO of an Irish wave energy converter firm emphasised the recognition to orientate development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. To achieve a satisfactory technology reliability record, experts recommend to put more focus on reliability in system design and to introduce “reliability modelling”. In the course of the design and deployment of marine energy converters, regular system functionality checks focusing on the final operation in open sea, grid-connected, multi-device arrays are recommended. As a main risk factor for reaching commercial generation, senior members of classification societies stressed the uncertainty about reliability and emphasised the need to focus on it.

### B. Standardisation

When being asked about the most valuable experience gained by the “early movers”, a project developer’s head of offshore named the “experienced negative impact by missing



standardisation". Considering the urgent need for consensus over standardisation, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). Another interviewee summed up the situation by saying "no standards, no results". According to the opinion of a utility's marine energy project manager, one of the top-priority tasks in the work of academia and research should be to concentrate on multi-applicable technologies, standardised devices and system components.

### *C. Technology Convergence*

As marine energy innovation activities are spread over a wide variety of concepts and components, the lack of design consensus is likely to restrict the pace of development and learning [30]. On the other side, Jacobsson and Bergek [41] emphasise potential longer-term advantages by retaining design variety. In the course of the performed interviews, two main philosophies characterising technological advancement were detected: (i) incremental innovation; and (ii) radical innovation. With a focus on technology convergence in marine energy, Jeffrey et al. [42] emphasise the need for supporting both, incremental and radical innovation, in parallel. Incremental innovation is relevant for closest-to-market full-scale prototypes and radical innovation for technologies with potential for step-change performance improvements. In a research on product development by Augustine et al. [43], it was concluded that a robust approach for systematic improvement is to combine the strengths of all available concepts instead of selecting the best among alternatives. Kaplan and Tripsas [44] describe that the evolution of technology is influenced by institutional actors (government agencies, media, standard bodies, industry associations) and outline that in case "a collective technological frame does not emerge", the convergence on a dominant design might be prevented. Teece [45] outlines that once a dominant design has emerged, competition shifts to a new set of parameters of which the most important one is cost.

### *D. Knowledge Sharing*

The limited sharing of knowledge in the industry and between project developers is seen by the strategy manager of a public-private partnership and the head of energy of UK's innovation agency as one main reason why the marine energy sector has not developed more rapidly. A senior policy officer of the Scottish Government emphasised the need to transfer lessons learnt in the offshore wind industry in order to avoid duplication of time and effort. The project manager for the implementation of the world's first commercial breakwater wave power plant underlined the need to improve the sharing of bad experience and testing data. To support progress, his position is to inform at conferences as far as practicable about experienced complications, to explain why things went wrong and to display the finally implemented solution.

### *E. Offshore Deployment Experience*

With the aim to demonstrate the viability of electricity generation by marine energy, it is required to provide transparency to investors and to focus on "bringing some

10 MWs in the water" as the programme director of a leading UK centre of sustainable energy expertise and pioneering project delivery outlined. Especially the importance to design for installation and maintenance purposes was emphasised by the representative of a wave energy converter manufacturer. As lessons learnt in the offshore oil & gas industry to be transferred to marine energy, a senior manager at a Canadian utility mentioned their focus on reliability and survivability.

### *F. Optimised Risk Sharing*

The development manager of an Irish wave energy converter firm explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He stressed the requirement to share risks by collaboration and to fully integrate risk management into project management. A UK-based law firm's contract expert highlighted that risk sharing shall be contractually optimised to identify the most appropriate risk owners. Apart from the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms) he recommended contract splitting (e.g. in fundament, turbine, transformer station, cabling) as done in offshore wind. An owner's representative even underlined that engineering consultancies shall share risk with project developers. Similarly, a device manufacturer's executive outlined that engineering consultancies shall share risk with industry. The implementation of appropriate risk sharing between the stakeholders is seen as highly relevant for achieving efficient progress in the sector. The experience in negotiating risk sharing is seen as a valuable outcome by the activities of the front-running companies.

### *G. Separating Between Detail and Dynamic Complexity*

To ensure continuous progress on the way towards competitive electricity generation, diverse problem-solving competences are required. In order to identify an optimum strategy before making a decision, the apparent problem complex needs to be analysed and categorised. On one side, we encounter technical difficulties that require profound engineering expertise, whereat other tasks – of more strategic nature – require qualitative assessment and tactical skills [46]. The complexity correlated with the market launch of marine energy can be sub-divided into:

a) Detail (or combinatorial) complexity, which is characterised by many interacting elements and a large number of combinatorial possibilities. In the context of marine energy, questions on detail complexity arise in the framework of machinery design or interface topics. The application of complexity-reducing measures is expedient [47] and might favour: (i) applying systems engineering; (ii) forcing standardisation; and (iii) using multi-applicable technologies.

b) Dynamic complexity, which is characteristic for large-scale engineering and construction projects with multiple feedback-processes and non-linear relationships with accumulation or delay functions. Cause and effect can be subtle and obvious interventions can produce non-obvious consequences [48]. Concerning the process of marine energy

commercialisation, dynamic complexity becomes apparent when looking at the long-term development history of the sector and the experienced setbacks. As for dynamically complex situations, a reduction of complexity can be counter-productive, qualitative feedback modelling is seen as the preferred approach [49]. Within the present study, this was realised by means of system-dynamics-backed analyses of semi-structured expert interview data.

Research revealed that in conventional management, mainly aspects of detail complexity are considered but that the real leverage lies in understanding dynamic complexity [50]. Most industrial planning tools and analytical methods are not equipped to handle dynamic complexity [51].

## X. CONCLUSION

Electricity generation by tidal stream or wave power arrays represents a radical innovation and is confronted by significant technological and financial challenges. The two top-ranked risks for multi-megawatt projects are identified as “achieving funding” and “uncertainty in device performance”. As investor confidence mainly depends on the proof of continuous grid-connected operation, both risk complexes are directly interlinked. Advantageously, they will be mitigated simultaneously when achieving the “array-scale success” as the central milestone on the way towards commercial generation. As by this game-changing event, the marine energy risk profile will be lowered and thus new investment attracted, the successful development of the industrial sector essentially depends on this mid-term goal.

Major power projects are usually realised by institutional financing and under the terms of international competitive bidding. Consequently, in marine energy, a number of equally competent manufacturing firms will be required at the time of the wholesale market-rollout to ensure realistic pricing and to avoid single bidder dependency. With the prospect of making profit in a newly created power market segment in the course of the regular implementation of utility-scale projects, a strong motivation for more cooperative interaction in the industry aiming on jointly de-risking the technology should be given.

To fulfil both requirements, i.e. (i) to achieve the market breakthrough; and (ii) to establish a new industry with a variety of manufacturers, extraordinary concessions between “natural competitors” are required. The (temporary) joining of forces in the form of competitive collaboration is necessary to pass the singular hurdle of getting market acceptance and to create investor confidence. It shall be kept in mind that the available “incubation rooms” were created with the goal to develop the technology to a level of reliability required to compete in the energy market. A special level of collaborative behaviour in a test field environment is beneficial to the sector.

After the decade-long marine energy development process with larger than expected delays and setbacks, capital investors are extremely reserved. In case first commercial array projects would not deliver good returns for investors, it can be expected that the significant industry investment of the last years might not be compensated and that the focus of interest finally moves to other technologies. Considering a

business environment in which other renewables operate price-competitive to conventional sources and the appearance of new forms of hydrocarbon extraction, the market entry of marine energy is seen as a one-off chance. It is evidently in the interest of all stakeholders in marine energy to overcome the present pre-profit phase and to establish this new industry.

## XI. ACKNOWLEDGEMENT

The study is part of a PhD research into strategic risk management for marine energy at the Institute for Energy Systems, University of Edinburgh, UK. The first author is grateful to Prof Bryden and Prof Harrison for their support and inspiring discussions. Thanks to all interview participants and anonymous reviewers for providing helpful suggestions.

## XII. REFERENCES

- [1] European Ocean Energy Association (2013) *Industry Vision Paper*, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [2] Siemens (2014) *Siemens says tidal sector too “niche”: MCT put on selling block*, [www.tidaltoday.com](http://www.tidaltoday.com) [26/11/2014]
- [3] Bucher, R. & Bryden, I. (2014) *Overcoming the marine energy pre-profit phase*, Asian Wave and Tidal Energy Conference, Tokyo, Japan
- [4] Bucher, R. (2013) *Strategic risk management in marine energy: A system dynamics approach to the evaluation of 40+ expert interviews*, 10<sup>th</sup> European Wave and Tidal Energy Conference, Denmark
- [5] Geels, F.W. (2004) *From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory*, Research Policy 33, pp897–920
- [6] Masini, A. & Menichetti, E. (2012) *The impact of behavioural factors in the renewable energy investment decision making process*, Energy Policy 40, pp28–38
- [7] Carlsson, B. et al. (2002) *Innovation systems: Analytical and methodological issues*, Research Policy 31, pp233–245
- [8] Alkemade, F., Kleinschmidt, C. & Hekkert, M. (2007) *Analysing emerging innovation systems: A functions approach to foresight*, International Journal of Foresight and Innovation Policy 3, pp139–68
- [9] Negro, S.O. et al. (2012) *Why does renewable energy diffuse so slowly? A review of innovation system problems*, Renewable and Sustainable Energy Reviews 16, pp3836–3846
- [10] Andersson, B.A. & Jacobsson, S. (2000) *Monitoring and assessing technology choice: The case of solar cells*, Energy Policy 28, pp1037–1049
- [11] Nelson, R.R. (1989) *Understanding technical change as an evolutionary process*, Journal of Economic Behavior & Organization 11(3), pp450–453
- [12] Steinhilber, S., Wells, P. & Thankappan, S. (2013) *Socio-technical inertia: Understanding the barriers to electric vehicles*, Energy Policy 60, pp531–539
- [13] Bergek, A., Hekkert, M. & Jacobsson, S. (2008) *Functions in innovation systems: A framework for analysing energy system dynamics*, Institute for Management of Innovation and Technology, Working Paper No. 84426-008
- [14] Erickson, W.B. & Maitland, I. (1989) *Healthy industries and public policy*, Dutton, M.E. (ed.), Pergamon Press, New York
- [15] Geels, F.W. & Kemp, R. (2007) *Dynamics in socio-technical systems: Typology of change processes and contrasting case studies*, Technology in Society 29(4), pp441–455
- [16] Bucher, R. & Jeffrey, H. (2014) *Creation of investor confidence: The top-level drivers for reaching maturity*, 5<sup>th</sup> International Conference on Ocean Energy, Canada
- [17] Yoshino, M.Y. & Rangan, U.S. (1995) *Strategic alliances: An entrepreneurial approach to globalization*, Harvard Business School Press, Boston, USA
- [18] Hamel, G. et al. (1989) *Collaborate with your competitors and win*, Harvard Business Review 67(1), pp133–139
- [19] Hull, F. & Slowinski, E. (1990) *Partnering with technology entrepreneurs*, Research Technology Management (11/12), pp16–20

- [20] Larsson, R. et al. (1998) *The inter-organizational learning dilemma: Collective knowledge development in strategic alliances*, Organization Science 9(3), pp286–305
- [21] Stiles, J. (1995) *Collaboration for competitive advantage: The changing world of alliances and partnerships*, Long Range Planning 28(5), pp109–112
- [22] Proff, H. (2013) *Geschäftsmodelle zwischen technischen Herausforderungen und betriebswirtschaftlichen Notwendigkeiten*, Axel Springer Group, <http://dx.doi.org/10.1007/978-3-658-01817-7>
- [23] Daimler (2013) *Daimler, Nissan, Ford join forces to develop affordable FCEVs*, Fuel Cells Bulletin 2, Elsevier Ltd., pp2–3
- [24] Toyota (2015) *Toyota to give away fuel-cell patents to boost industry*, Agence France Presse, [www.businessinsider.com](http://www.businessinsider.com) [06/01/2015]
- [25] Tesla (2014) *All our patents belong to you*, [www.teslamotors.com](http://www.teslamotors.com) [07/01/2015]
- [26] Håkansson, H. (1990) *Technological collaboration in industrial networks*, European Management Journal 8(3), pp371–379
- [27] Hekkert, M.P. (2007) *Functions of innovation systems: A new approach for analysing technological change*, Technological Forecasting & Social Change 74, pp413–432
- [28] Negro, S.O. et al. (2007) *Dynamics of Technological Innovation Systems*, Dissertation, Netherlands Geographical Studies 356, ISSN: 0169-4839, Utrecht University
- [29] Wyatt, S. (2014) *Financing marine energy: The role of innovation in reducing risk*, 5<sup>th</sup> International Conference on Ocean Energy, Canada
- [30] Jay, B. & Jeffrey, H. (2010) *UKERC research atlas topic: Marine energy*, UK Energy Research Centre, London
- [31] Isoraitè, M. (2009) *Importance of strategic alliances in company's activity*, Intellectual Economics 1(5), ISSN 1822-8011, pp39–46
- [32] Leete, S. et al. (2013) *Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences*, Energy Policy 60, pp866–875
- [33] Talke, K. (2005) *Einführung von Innovationen: Marktorientierte strategische und operative Aktivitäten als kritische Erfolgsfaktoren*, ISBN 978-3-8350-0069-8
- [34] Corsatea, T.D. (2014) *Increasing synergies between institutions and technology developers: Lessons from marine energy*, Energy Policy 74, pp682–696
- [35] Bucher, R. (2012) *De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine*, 4<sup>th</sup> International Conference on Ocean Energy, Ireland
- [36] SI Ocean (2014) *Wave and tidal energy strategic technology agenda*, [www.si-ocean.eu](http://www.si-ocean.eu) [19/06/2015]
- [37] SI Ocean (2014) *Wave and tidal energy market deployment strategy for Europe*, [www.si-ocean.eu](http://www.si-ocean.eu) [19/06/2015]
- [38] D. Magagna, D. & Uihlein, A. (2015) *Ocean Energy Development in Europe: Current status and future perspectives*, International Journal of Marine Energy 56, <http://dx.doi.org/10.1016/j.ijome.2015.05.001>
- [39] Bonar, P.A.J., Bryden, I. & Borthwick, A.G.L. (2015) *Social and ecological impacts of marine energy development*, Renewable and Sustainable Energy Reviews 47, pp486–495
- [40] MacGillivray, A. et al. (2014) *Innovation and cost reduction for marine renewable energy: A learning investment sensitivity analysis*, Technological Forecasting & Social Change 87, pp108–124
- [41] Jacobsson, S. & Bergek, A. (2004) *Transforming the energy sector: The evolution of technological systems in renewable energy technology*, Industrial and Corporate Change 13(5), pp815–849
- [42] Jeffrey, H. et al. (2013) *Accelerating the development of marine energy: Exploring the prospects, benefits and challenges*, Technological Forecasting & Social Change 80, pp1306–1316
- [43] Augustine, M. et al. (2010) *Concept convergence: A framework for improving product concepts*, Industrial Engineering 59, pp367–377
- [44] Kaplan, S. & Tripsas, M. (2008) *Thinking about technology: Applying cognitive lens to technical change*, Research Policy 37(5), pp790–805
- [45] Teece, D.J. (1986) *Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy*, Research Policy 15(6), pp285–305
- [46] Bucher, R. & Bryden, I. (2014) *Strategic orientation for ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge*, Journal of Energy Challenges and Mechanics 1(2), ISSN 2056-9386, pp1–10
- [47] Groesser, S. (2011) *Projects often fail because of dynamic complexity: Managing complexity by qualitative feedback modelling*, Bern University of Applied Sciences, [www.bfh.ch](http://www.bfh.ch) [10/03/2013]
- [48] Sterman, J.D. (1992) *System dynamics modelling for project management*, Sloan School of Management, Massachusetts Institute of Technology, Cambridge
- [49] Cooper, K. & Lee, G. (2009) *Managing dynamics of projects and changes*, International System Dynamics Conference, USA
- [50] Sterman, J.D. (2010) *Does formal system dynamics training improve people's understanding of accumulation?*, System Dynamics Review 26(4), pp316–334
- [51] Senge, P. (1990) *The fifth discipline: The art and practice of the learning organisation*, ISBN 978-0553456349, Crown Publishing Group, New York

### XIII. APPENDIX A

TABLE IV  
LIST OF PARTICIPATING STAKEHOLDERS

<b>Government (Associations) &amp; Trade Organisation:</b> Scottish Government, Marine Scotland, Energy Technologies Institute, Carbon Trust, DECC, The Crown Estate, Scottish Natural Heritage, Centre for Environment, Fisheries & Aquaculture Science, RenewableUK, Technology Strategy Board.
<b>Certifying Authorities:</b> Det Norske Veritas, Lloyd's Register.
<b>Investors &amp; Lenders:</b> Green Giraffe.
<b>Law Firms:</b> Eversheds International.
<b>Academia &amp; Research:</b> University of Washington, University of Edinburgh, National Taiwan Ocean University, Irish Marine Institute.
<b>Engineering Consultancies:</b> Natural Power, Xodus, Tecnalia Research & Innovation, South West Renewable Energy Agency, Royal Haskoning.
<b>Project Developers:</b> Emera, EDF, Electricity Supply Board, Iberdrola.
<b>Owners &amp; Operators:</b> ScottishPower Renewables, Ente Vasco de Energía.
<b>Transmission System Operator:</b> Scottish & Southern Energy Renewables.
<b>Device Manufacturers:</b> Marine Current Turbines, Pelamis Wave Power, Wavebob, Siemens, Wave Star, Ocean Renewable Power Company.
<b>Test Site Operators:</b> EMEC, Fundy Ocean Research, National Renewable Energy Centre, Minas Basin Pulp & Power, France Energies Marines.
<b>NGO:</b> Greenpeace.
<b>Offshore Wind Industry:</b> Dong Energy Power.



## **F Publications**

### **F.3 Peer review conference papers**

Bucher, R., Jeffrey, H. (2014) Creation of investor confidence: The top-level drivers for reaching maturity, Proceedings of the 5<sup>th</sup> International Conference on Ocean Energy (ICOE), Halifax, Canada

# CREATION OF INVESTOR CONFIDENCE: THE TOP-LEVEL DRIVERS FOR REACHING MATURITY

Ralf Bucher<sup>\*1</sup>, Henry Jeffrey<sup>2</sup>

Institute for Energy Systems, University of Edinburgh  
Kings Buildings, Mayfield Road, Edinburgh EH9 3JL, United Kingdom

<sup>\*</sup>Corresponding author, Tel.: +49 157 72943159

E-mail addresses: <sup>1</sup>R.Bucher@sms.ed.ac.uk, <sup>2</sup>Henry.Jeffrey@ed.ac.uk

## ABSTRACT

**Marine energy finds itself in a decisive transition phase with successfully tested full-scale prototypes but an outstanding proof of the technological concept. In the course of an interview series with 44 experts from 13 stakeholder groups, the top-ranked risks for utility-scale tidal stream and wave power projects were identified as “achieving funding” and “uncertainty in device performance”. A system dynamics computer model built one-on-one to 234 received interview replies on the reinforcing and countervailing effects on the final objective of full-commercial electricity generation revealed the importance to “showcase commercial-scale projects / successful demonstrators”. The development of the marine energy sector depends on transparently achieving the “array-scale success” as the interim milestone by which the risk profile will be lowered and required investment attracted.**

**Keywords:** Marine energy commercialisation, investor confidence, array-scale success, system dynamics modelling.

## 1. INTRODUCTION

The private sector investment in marine energy technologies of over 600 million euros in the last 7 years has triggered significant progress and helped tidal current and wave power to progress towards commercialisation. Based on the successful testing of full-scale prototypes, pioneering tidal arrays are presently implemented by direct agreements between developers/investors and leading device

manufacturers. Before becoming recognised as a fully mature and competitive electricity generation method, marine energy needs to prove a range of referencable application cases. The attainment of this confidence-building “array-scale success” will represent a major turning point for the global marine energy business and is expected to finally trigger large-scale deployment.

In the course of this research, the interviewed experts provided estimations for risk levels focusing on the realisation of virtual tidal current or wave power reference projects (capacity ~40 MW, implementation ~2025, investment ~120 m€). The top-ranked risks were identified as “achieving funding” and “uncertainty in device performance” (i.e. “reliability”).

## 2. OBJECTIVE OF THE RESEARCH

Considering a business environment in which other renewables operate price-competitive to conventional sources and the appearance of new forms of hydrocarbon extraction, the market entry of marine energy is a one-off chance. The top-level driving factors for achieving full-commercial power generation by marine energy were recently determined in the course of a system dynamics-backed analysis of cross-category expert interview data, as: (i) strong and long-term commitment from government; (ii) array-scale success; and (iii) cost reduction [1].

As the singular characteristics of government regulations are outside the range of the present research, focus is put on the interim milestone “array-scale success”. The effective preparation and conduction of this game-changing event is seen as the decisive strategic task at the time by

which the risk profile will be lowered and required investment attracted.

To rapidly overcome the present pre-profit phase, the strategic orientation of the central stakeholders needs to be regularly evaluated in order to identify joint objectives and to put corresponding measures put into practice.

### 3. PRINCIPLES AND METHODOLOGY

This background research focusses on de-risking the commercialisation of large-scale electricity generation by tidal stream and wave power. A key principle applied is to integrate a wide spectrum of positions in a transparent and holistic manner. As such, new insight is created by compiling different sources of knowledge for the elaboration of an optimum strategy towards market-competitive electricity generation. Based on this multi-disciplinary attempt, an all-encompassing appraisal becomes possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests. Mechanisms able to accelerate the market entry of marine energy require the close coordination of activities by the technology, policy or financing sectors. The present work represents a dynamic interplay between knowledge creation, knowledge compression and targeted knowledge diffusion.

For the underlying survey, a questionnaire with a total of 90 questions was elaborated out of which 48 were yes/no questions and 42 of qualitative character referring to stakeholder-related experience. By contacting 136 representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups (see Appendix A) was retained for the analysis, corresponding to an effective return rate of 32.4 % which is more than usual for studies of this nature [2]. A total number of 2,129 individual replies had to be grouped to formulate higher-level correlations as basis for the computer-based system dynamics modelling. All semi-structured single person interviews were conducted either face-to-face at the premises of the interviewee or by telephone between June 2012 and April 2013.

Huang & Newell [3] examine in their research knowledge management within large organisations and the characteristics of cross-functional project implementations. They point out that it is vital to understand the dynamics of organisational learning and strategic change initiatives, especially when multiple stakeholder groups are involved. To master the amount and complexity of the cross-category information and to systematically identify the fundamental drivers, in the present study all data were uniformly consolidated and form as such the basis for the configuration of detailed cause-effect relationship diagrams. A key element of the methodology applied is to control the dynamic process based on reliable feedback information. The final system dynamics models emerge from “iterative cycles of data gathering, feedback analysis, implementation of measures and result evaluation” as described by Formentini & Romano [4] in a knowledge management context. The elaborated system dynamics computer models<sup>1</sup> are designed and configured exclusively based on the empirical data obtained through expert interviews. The result ranking calculated by the system dynamics simulation software represents superordinate knowledge and correlates to information usually available to management.

In the course of the study, the following chronological steps were taken: (i) conduction of expert interviews; (ii) grouping of replies; (iii) elaboration of representative system dynamics models; (iv) ranking of calculated impact factors; (v) determination of top-level driving factors; (vi) formulation of central interview statements; and (vii) elaboration of strategic principles to orientate the technology, policy and financing sectors.

For the present research, three system dynamics computer models were built. In an initial model, the top-level driving factors for the commercialisation of marine energy were identified. Based on the result to focus on “showcasing commercial-scale projects / successful demonstrators”, a corresponding and more detailed model was built. In order to cross-check and substantiate the research, in a third cause-effect relationship diagram, a diametrically opposite perspective was taken to gain new insight

<sup>1</sup> The system dynamics modelling software used in the present research is “Process Modeler” (version 7.5.8) by CONSIDEO GmbH, Germany.

by analysing the entity of hindering impacts on the marine energy development.

#### 4. INVESTOR CONFIDENCE

##### a. ATTITUDES TOWARDS WAVE AND TIDAL

Leete et al. [5] recently examined investors' attitudes and behaviours towards wave and tidal technologies. Of the investors engaged in venture capital funding, all revealed that they were unlikely to make any future investments in early stage device development. It is reported that private investors are not closed to the industry completely, but the current level of risk and uncertainty are discouraging them from investing at this time. Venture capital investors are discouraged from investing because of high capital requirements and the uncertainty of costs, respective future revenues. It is outlined that a track record of continuous device operation of at least 6 months is seen as a pre-requisite for further investments. The authors conclude that at the current stage of development, strategic investment in partnership with industry investors is essential for moving towards commercialisation.

Investors profiled by Masini and Menichetti [2] showed a clear preference for more mature, proven technologies with only 3 of 93 investors analysed having any exposure to wave and tidal energy. Given the small scale of current marine energy developments, investors are able to achieve similar or greater returns on larger developments of more proven energy technologies.

Santos et al. [6] emphasise that energy investments have specific characteristics because of (i) their irreversibility; (ii) pertaining high levels of uncertainty; and (iii) the flexible timing as the investor might be able to postpone his decision in order to obtain better information. The different funding sources over the technology development and maturation stages are summarised by Wuestenhagen and Menichetti [7] as: grants (for R&D), venture capital (for part-scale prototypes), private equity (for full-scale prototypes), debt finance (for first pioneering arrays) and institutional finance (for utility-scale projects).

Aside from the difficulties for venture capitalists to engage, the private company investment in marine energy technologies of over 600 m€ in the last 7 years has built confidence and

triggered significant progress [8]. The involvement of major industrials (such as ABB, Alstom, Andritz, DCNS, Siemens and Voith) as well as the successful testing of full-scale prototypes underlines the commitment in the sector and indicates significant engineering competence.

##### b. OTHER RENEWABLES: COST COMPARISON

According to DECC [9], the projected levelised cost of electricity generation (LCOE<sup>2</sup>) will range for UK marine energy in the year 2020 between 20 and 42 c€/kWh. Spain expects LCOE for that period of time of 21 to 33 c€/kWh [10]. Previsic et al. [11] have pointed in similar manner to commercial opening cost of electricity for wave power in the order of 20 to 30 c€/kWh. Until 2020, DECC projects LCOE for onshore wind in the UK of 9 to 15 c€/kWh and for offshore wind of 13 to 22 c€/kWh. RenewableUK believe that the current LCOE for leading tidal stream devices is around 36 c€/kWh compared with 48 c€/kWh for wave power devices [12].

As onshore wind energy represents the reference for cost-competitive renewable power, it shall be noted that the global average LCOE dropped from 19 c€/kWh in 1992 to 6 c€/kWh in 2014 [13]. Offshore wind farms at very good locations currently achieve LCOE of 11 to 19 c€/kWh [14].

Presently the kWh-cost in marine energy are far too high to compete with other renewable or even non-renewable generation options [15]. Taking into consideration the projected LCOE in the UK for 2020, the cost for tidal stream might touch the upper end of the offshore wind range. For the forthcoming years, governmental support programs will be indispensable to further drive research and development [16]. Referring to offshore wind – with a global installed capacity of 5.4 GW [17] – it is expected that still 15 years of further subsidies will be required [18].

Apart from purely assessing c€/kWh generation cost, a unique asset of renewable electricity generation by tidal currents is its predictability due to the known effects of gravitation exerted mainly by the moon and the sun upon the earth. Especially in grids with high portions of volatile

<sup>2</sup> LCOE is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.

renewable generation, grid operators would welcome such long-term and precisely predictable generation capacities. Especially at remote sites with weak grid systems, this might be an economically relevant factor. The overall performance of hybrid systems operating a combination of intermittent solar photovoltaic, wind and reserve-capacity diesel power could be improved.

### c. THE “ARRAY-SCALE SUCCESS”

Reliability is an important factor of success for all emerging technologies. In marine energy, the reliability proof remains a major challenge as most devices to date have been in the water only for short periods of less than one year. In the course of the expert interviews, the importance to focus on “array-scale activities” and “to get pilot farms built” was repeatedly stressed. Most answers to the question “In which areas is research most required to accelerate the development of marine energy?” referred directly to multi-device arrangements such as “array-scale design”, “hydrodynamic modelling of arrays”, “array-scale maintenance”, “the need for design tools to facilitate cost-effective array-scale development” and “to see first arrays progress through FID<sup>3</sup>”.

The “array-scale success” represents the key interim milestone and has to be seen within the larger picture, characteristic for the power industry. For the marine energy technology breakthrough, positive and transparent feedback from a variety of longer term grid-connected and commercially operated multi-megawatt arrays is required. In case first small-scale arrays become operational in 2016/17 as outlined in [11], then the achievement of the “array-scale success” – as per definition – can be expected in the first half of the new decade.

Because of the comprehensive demands on this interim milestone, the hurdle will not be passed by a small number of companies in the course of a singular demonstration project at one specific site. After the concept maturity will have been demonstrated by grid-feeding schemes, new potential for cost reduction will be tapped by serial manufacturing processes and due to learning effects forced by the routine implementation of projects under global market competition. The

identification of yet undiscovered low-cost strategies is expected as a natural element of technology convergence processes.

The prevailing top-ranked risks (as “achieving funding” and the “uncertainty in device performance”) are directly interdependent as investor confidence depends on track records of continuous device operation. In the centre of this area of conflict we find the “array-scale success” because passing this milestone will give confidence in the industrial sector and de-risk investments in commercial projects. As the preparation and management of the “array-scale success” is of central relevance for the continuous development of the marine energy, effort was put in identifying the top-level strategic principles of technical-organisational nature for being considered to be implemented by the key stakeholders.

## 5. DRIVERS FOR REACHING MATURITY

### a. THE TECHNOLOGY SECTORS

#### i. SYSTEMS ENGINEERING APPROACH

When asking for significant potential to get the cost for utility-scale project implementations down, the CEO of an Irish wave energy converter manufacturer emphasised the clear recognition to orientate their development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. To achieve a satisfactory technology reliability record, experts recommended to put more focus on reliability in system design and to introduce reliability modelling. In the course of the design and implementation process of the ocean energy converters regular system functionality checks focusing on the final operation in open sea grid-connected multi-device arrays shall be performed. As main factors for reaching commercial generation, two senior members of classification societies stressed uncertainty about reliability and the need to focus on it.

#### ii. MULTI-APPLICABLE TECHNOLOGIES AND JOINT CONCEPTS

According to the opinion of a utility’s ocean energy project manager, one of the top-priority tasks in the work of academia & research should be to concentrate on multi-applicable technologies and standardised devices and components (e.g. moving parts, cable connector systems, control

<sup>3</sup> Final Investment Decision (see “FID enabling for renewables” by DECC)



interfaces). To finally ensure identical component delivery, effective supply chain management and leveraging logistics is required.

### iii. STANDARDISATION

The reply of a project developer's head of offshore when asking for the most valuable experience gained by the early movers, was the "experienced negative impact by missing standardisation". Considering the urgent need for consensus over standardisation, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). One interviewee summed up the situation as "no standards, no results".

### iv. TECHNOLOGY CONVERGENCE

As marine energy innovation activities are spread over a wide variety of concepts and components, Jay and Jeffrey [19] outline that the lack of design consensus is likely to restrict the pace of development and learning. On the other side Jacobsson and Bergek [20] emphasise potential longer-term advantages by retaining design variety. In the course of this survey, two main philosophies characterising technological advancement were detected: (i) selecting the best among alternatives or combining the strengths of all available concepts; and (ii) incremental or radical innovation. In the research on technology convergence by Augustine et al. [21] it is concluded that a robust approach for systematic improvement is to combine the strengths of all available concepts instead of selecting the best among alternatives. The need for supporting incremental and radical innovation in parallel is emphasised by Jeffrey [22]. Incremental innovation is relevant for closest-to-market full-scale prototypes and radical innovation to technologies with potential for step-change performance improvements. Teece [23] outlines that once a dominant design has emerged, competition shifts to a whole new set of variables of which the most important one is price. Examples are provided that "imitators" can make higher profit on the long-term than the original firms first commercialising a new product or technology. In the course of the interviews a utility's representative underlined the expectation to get the cost for commercial-scale project implementations down by the positive impact of technology convergence.

### v. KNOWLEDGE SHARING

The limited knowledge sharing by the industry and project developers is seen by the strategy manager of a public-private partnership and the head of energy of UK's innovation agency as a main reason why the ocean energy sector has not developed more rapidly. A senior policy officer of the Scottish government emphasised the need to transfer lessons learnt in the offshore wind industry in order to avoid duplication of time and effort. The project manager for the implementation of the world's first commercial breakwater wave power plant outlined that the need to improve the sharing of bad (!) experience and testing data is key. To support progress, his position is to inform (as far as possible) about such complications at conferences, to explain why things went wrong and to display the finally implemented solution.

### vi. MAXIMISING COLLABORATION AND MINIMISING COMPETITION

In line with the findings on limited sharing of knowledge, a lack of collaboration was reported. The artificial competition with on-/offshore wind was criticised by an Irish ocean energy development manager as negatively influencing an uninterrupted progress. The interviewed head of development of a wave energy device manufacturer underlined the attractiveness of exploring the prospects by combining wave and wind power.

### vii. OFFSHORE DEPLOYMENT EXPERIENCE

With the aim to demonstrate the viability of electricity generation by ocean energy, it is required to provide transparency to investors and to focus on "bringing some 10 MWs in the water" as the programme director of a leading UK centre of sustainable energy expertise and pioneering project delivery outlined. Especially the importance to design for installation and maintenance purposes was emphasised by the representative of a wave energy converter manufacturer. As lessons learnt in the offshore oil & gas industry to be transferred to ocean energy, a senior manager at a Canadian utility mentioned their focus on reliability and survivability.

### viii. COMPETITIVE COLLABORATION

Hull and Slowinski [24] demonstrate that co-operative relationships between firms in high

technology can bring to market new innovations that neither firm alone could have accomplished. Especially for firms which are not part of the group of ocean energy front-runners, new inter-firm collaborations offer potential to prepare for global competition. The term “competitive collaboration” was introduced by Hamel et al. [25] for strategic alliances that strengthen companies against outsiders (i.e. other renewables) even as they weaken each partner vis-à-vis the other.

Jay and Jeffrey [19] describe that in the marine energy sector there are a number of technologies and components, such as foundations, moorings, marine operations and resource assessment, which offer opportunities for shared/collaborative learning. They underline that support and transfer of generic knowledge is limited by commercial competition.

Ocean energy needs to assert its position in the competitive renewable energy market. Regular commercial projects will finally be realised under established international procurement principles for which a number of similarly competent industrial bidders is required. In case natural competitors accept the high significance of jointly achieving the identified intermediate milestone “array-scale success”, the motivation for inter-firm alliances will rise. Exemplary strategic alliances on how to develop new products and to penetrate new markets can serve as references. The benefits by inter-firm co-operations need to be individually examined in the course of risk/reward assessments. In a recently published paper from the European Ocean Energy Association [26], clear reference was given towards Airbus which was classified as a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments. Amanatidou & Guy [27] emphasise the increasing importance of knowledge-based industries and focus on aligning existing perceptions by maximising collaboration and minimising competition.

#### **ix. OPTIMISED RISK SHARING**

The development manager of an Irish wave energy converter manufacturer explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He stressed the requirement to share risks by collaboration and to

fully integrate risk management into project management. A UK law firm contracts expert highlighted that risk sharing shall be contractually optimised to identify the most appropriate risk owners. Apart from the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms) he recommended contract splitting (e.g. in turbines, fundament, transformer station, inner-park cabling) as in offshore wind. An owner’s representative even recommended that engineering consultancies shall share risk with project developers. Similarly a device manufacturer’s executive outlined that engineering consultancies shall share risk with industry. The implementation of appropriate risk sharing between the stakeholders is seen as highly relevant for achieving efficient progress in the sector. The experience in negotiating risk sharing is seen as a valuable outcome by the activities of the front-running companies.

#### **x. CERTIFICATION FOR MARKET-READINESS**

Third-party certification is well established in mature industries and means that an independent organisation confirms the compliance of a product or service with legal-normative standards, contractual obligations and project-specific technical requirements. In the context of proving the “array-scale success”, the integrity assessment of the technological concept – and as such type and project certification – are required. In the course of the performed expert interviews, a global certification company’s representative underlined the importance of certification but also mentioned the need to accelerate the development of robust and reliable marine energy technology and recommended as such to carefully balance progress with a level of risk acceptable to all involved stakeholders.

#### **xi. INSTALLED CAPACITY / CAPACITY FACTOR**

The principal scientist of a UK wave power developer underlined that the cost of energy production is dependent on the capacity deployed. In Bucher [28] this relationship was examined for an envisaged 600 MW tidal array in Korea. Based on a full lunar cycle 3D tidal regime model, detailed statements on optimising the “installed capacity / capacity factor”-ratio and consequently limiting the financial risk could be made. The

possibility to select a preferred ratio of capital investment to profit widens the circle of potential investors and helps to effectively de-risk early-stage project initiatives.

## **xii. TECHNOLOGY QUALIFICATION ROUTINE**

The interview participants identified reliability concerns as the top-ranked non-commercial risk and poor liability was mentioned as key operational risk. The widespread perception of high cost and unproven reliability in marine energy was mentioned by the strategy manager of a public-private partnership as negatively influencing the sector. A US academic named the need for longer baselines for systems reliability and an R&D vice-chair outlined that (currently) reliability is more important than efficiency. The managing director of a UK financial firm and the vice president of a Canadian project developer emphasised that concerns for delays and cost-overruns mainly relate to reliability, durability and performance of ocean energy converters. According to a Scottish government employee, the failure of devices was the fundamental and greatest single reason for projects being delayed or cost increase. Reasons why the ocean energy sector has not developed more rapidly were repeatedly identified in the uncertainty of device performance and reliability. The requirement to demonstrate equipment reliability at utility-scale devices was formulated by the machinery manager of a global maritime classification society. The division head of an Irish state agency replied to the question on where research is most required, to accelerate the development of marine energy and that reliability and integrity of devices are essential.

As years will pass until full concept maturity will be reached, Bucher [29] proposed for early commercial project implementations a “competitive technology qualification routine” to achieve the required safety for investment. The principal idea is to extend the execution of utility-scale projects by a qualification procedure in the course of which different manufacturers’ power conversion devices are deployed and operated in real-sea conditions in the final project area for a defined period of time. The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated. The

competitive technology qualification routine represents a transparent and evidence-based selection procedure to identify the most suitable technology for a site.

## **xiii. DETAIL AND DYNAMIC COMPLEXITY**

The market entry of marine renewables and their integration into existing grid systems represents an ambitious undertaking in a dynamic but long-term oriented business environment. When asking for measures to increase equipment reliability, a renewable energy consultant recommended to “design out complexity / failure points”. For managing complexity, the differentiation between detail (or combinatorial) and dynamic complexity as per the complex systems theory [30] is helpful:

1. Detail complexity is characterised by many elements and a large number of combinatorial possibilities. Groesser [31] explained that in detail-complex situations, methods to reduce complexity might be useful. In the present context potential to reduce detail complexity is seen in applying systems engineering, standardising components and using multi-applicable technologies. When taking a look at the wider picture, a reduction of detail complexity could be for example achieved in commercial project implementations by introducing the described “competitive technology qualification routine”. The long-term best-performing system would be identified in a comprehensive and transparent way.

2. Dynamically complex systems contain non-linear feedback, time delays and accumulations. Cause and effect are subtle and obvious interventions can produce non-obvious consequences. It might arise even in simple systems and can usually not be reduced but managed. Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships and the need to integrate hard and soft data [32,33]. The process of commercialising ocean energy comprises high dynamic complexity, for example because of the continuously varying interaction between heterogeneous stakeholders over a decade’s long period of time. In order to improve project success rates, Groesser [31] recommends



qualitative feedback modelling as a method to analyse and manage dynamic complexity.

Research revealed that in conventional project management mainly aspects of detail complexity are considered [34]. Senge [35] underlines that the real leverage in the majority of management situations lies in understanding dynamic complexity. According to his research, most established planning tools and analysis methods are designed to manage detail complexity but are not equipped to handle dynamic complexity.

## **b. THE POLICY SECTOR**

With regard to policy-related aspects, a key topic is to enable efficient consenting, leasing and licensing by ensuring a single point of handling. The close and regular adaptation of public support programmes and incentive mechanisms to actual requirements is crucial for accelerating the marine energy maturation process. Apart from publishing procedures on how to certificate devices, support in the elaboration of templates and a general refinement of the consenting process is necessary.

The need to bring in existing skills from the oil & gas sector, to improve knowledge sharing and to strengthen collaboration between industry, utilities, academia, device manufacturers and project developers was identified. The implementation of appropriate risk sharing mechanisms between the stakeholders is relevant for achieving common progress.

In order to prepare the move from device testing towards array-scale activities under open sea conditions, grid-connected test facilities and pilot zones are of high value. Considering future large-scale deployments, the importance of transmission infrastructure investments and support strategies for grid operation with significant wave and tidal in-feed cannot be underestimated.

With regard to the global scale of the industry, simplified access to the international (out of Europe) markets is important.

## **c. THE FINANCING SECTOR**

Apart from the support for technologies with declared synergies toward off-shore wind, the financing sectors should focus on stimulating the cross-interaction between the different forms of renewable energies and on strengthening design convergence.

The cost of marine energy is high compared to existing generation with hidden subsidies. It is necessary to “accept that offshore intervention is expensive” and to realise the “outrageously expensive deployment costs”. As cost of energy was identified to be more relevant than CapEx spending, efforts are required to identify the techno-economic optimum way for the harvesting of marine energy. Continuous cost reduction is expected by economies of scale. With regard to the mentioned need to compromise reliability and cost, the insurability of the projects must be ensured. In feasibility studies it is important to consider that the cost of energy production is dependent on the capacity deployed [28].

To enable efficient project implementations, a focus must be on limiting the presently high level of claims. The advantage of working with already existing companies in the market goes in line with the need to improve contract structuring and contract standardisation as in on-/offshore wind. In the course of a project planning, it is required to foresee extreme engineering and to consider the likelihood of test- or early-stage failures. Pilot projects with availability records will provide confidence in the performance of the core technologies.

Generally it is required to keep in mind that realism is requested when it comes to the (global) scale of the industry and to recognise the differences to offshore oil & gas with regard to design, manufacturing and logistics.

## **6. CONCLUSION**

In the past years there might have been over-optimistic predictions by developers trying to persuade investors combined with an underestimation of the technical challenges and a lack of exchange of experience. Generally, the introduction of electricity generation by tidal stream and wave energy represents an unprecedented initiative with high investment requirements and significant risks involved.

The principal objective of this research is to create consolidated strategic knowledge to support orientating the marine renewable energy maturation and commercialisation process. The prevailing top-ranked risks (“achieving funding” and “uncertainty in device performance”) are directly interdependent as investor confidence

mainly depends on track records of continuous device operation. In the centre of this area of conflict we find the “array-scale success”. Passing this milestone will give confidence in the industrial sector and de-risk investments. As the targeted preparation and management of this “array-scale success” is of central relevance for the steady development, the top-level strategic principles of technical-organisational nature were elaborated based on the system dynamics results and the correlated expert interview statements.

To systematically improve the reliability on array-scale, the presented strategic principles are of relevance for reaching market readiness. The listing can serve as reference guideline for developers seeking capital or for investors to judge the risk-to-reward ratio of investment options and to see if a candidate follows solid strategic principles.

Even as it should be in the joint interest of all market participants to showcase that the technology performs reliably, the presently limited sharing of knowledge and experience is seen as a main reason why the sector has not developed more rapidly. Synergies by collaboration and inter-firm alliances will facilitate achieving market competitiveness. Mutual long-term benefits will be generated after the sector has proven its maturity.

The presented approach of using cross-category interview data to create complex system dynamics computer models is seen as a powerful method to keep track of the development and to advance strategy finding. Even as detail complexity can be reduced by suitable methods to a certain degree, the key for success is seen in handling the involved dynamic complexity. The approach of “expert interviews / system dynamics modelling / application of strategic principles” provides an adequate fundament.

## ACKNOWLEDGEMENTS

The study is part of a PhD research into strategic risk management for marine energy projects at the Institute for Energy Systems, University of Edinburgh, UK. The author is grateful to the interview participants and Prof Bryden for his continuous support and inspiring discussions. Thanks to the anonymous reviewers for providing helpful suggestions.

## APPENDIX A

### List of participating stakeholders

Government (associations) & trade organisation: The Scottish Government, Marine Scotland, Energy Technologies Institute, Carbon Trust, Department of Energy and Climate Change, The Crown Estate, Scottish Natural Heritage, Centre for Environment, Fisheries & Aquaculture Science, RenewableUK, Technology Strategy Board.
Certifying authorities: Det Norske Veritas, Lloyd's Register.
Investors & lenders: Green Giraffe.
Law firm: Eversheds International.
Academia & research: University of Washington, University of Edinburgh, National Taiwan Ocean University, Irish Marine Institute.
Engineering consultancies: Natural Power, Xodus Group, Tecnalia Research & Innovation, South West Renewable Energy Agency, Royal Haskoning.
Project developers: Emera, EDF, Electricity Supply Board, Iberdrola.
Owners & operators: ScottishPower Renewables, Ente Vasco de la Energía.
Transmission system operator: Scottish and Southern Energy Renewables.
Device manufacturers: Marine Current Turbines, Pelamis Wave Power, Wavebob, Siemens, Wave Star, Ocean Renewable Power Company.
Offshore contractors: 6 contacted (no feedback).
Test site operators: European Marine Energy Centre, Fundy Ocean Research Centre for Energy, National Renewable Energy Centre, Minas Basin Pulp & Power, France Energies Marines.
NGO: Greenpeace.
Offshore wind industry: Dong Energy Power.
Oil & gas industry: 4 contacted (no feedback).

## REFERENCES

- [1] Bucher, R. (2013) Strategic risk management in ocean energy, Proceedings of the European Wave and Tidal Energy Conference, Aalborg, Denmark
- [2] Masini, A. & Menichetti, E. (2012) The impact of behavioural factors in the renewable energy investment decision making process: Conceptual framework findings, Energy Policy 40, pp28–38
- [3] Huang, J.C. & Newell, S. (2003) Knowledge integration processes and dynamics within the context of cross-functional projects, International Journal of Project Management 21, pp167–176
- [4] Formentini, M. & Romano, P. (2011) Using value analysis to support knowledge transfer in the multi-project setting, International Journal of Production Economics 131, pp545–560

- [5] Leete, S. et al. (2013) Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences, *Energy Policy* 60, pp866–875
- [6] Santos, L. et al. (2014) Real Options versus Traditional Methods to assess Renewable Energy Projects, *Renewable Energy* 68, pp588–594
- [7] Wuestenhagen, R. & Menichetti, E. (2012) Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research, *Energy Policy* 40, pp1–10
- [8] Industry Vision Paper (2013) European Ocean Energy Association, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [9] DECC (2011) UK renewable energy roadmap: Department of Energy & Climate Change, UK
- [10] IEA-OES (2013) Annual Report, Spain, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2014]
- [11] Previsic, M. et al. (2012) The future potential of wave power in the US, American Geophysical Union, Fall Meeting 2012, abstract #OS53D-08, [www.re-vision.net](http://www.re-vision.net) [06/04/2014]
- [12] RenewableUK (2013) Wave & tidal energy, [www.renewableuk.com](http://www.renewableuk.com) [accessed 13/02/2013]
- [13] Fraunhofer-ISE (2013) Levelised Cost of Electricity, Renewable Energy Technologies, [www.ise.fraunhofer.de](http://www.ise.fraunhofer.de) [06/04/2013]
- [14] International Renewable Energy Agency (2012) Renewable Energy Technologies: Cost Analysis Series, [www.irena.org](http://www.irena.org) [10/04/2014]
- [15] Previsic, M. & Shoele, K. (2013) Cost Reduction Pathways for Wave Energy, 10th European Wave and Tidal Energy Conference, Aalborg, Denmark
- [16] IEA-OES (2014) Ocean Energy Review of Supporting Policies, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2013]
- [17] IEA (2013) Technology Roadmap Wind Energy, [www.iea.org/publications](http://www.iea.org/publications) [06/05/2014]
- [18] Karikari-Boateng, K.A. et al. (2013) Reliability of Tidal Turbines using Wind Turbine Experience, Proceedings of the European Wave and Tidal Energy Conference, Aalborg, Denmark
- [19] Jay, B. & Jeffrey, H. (2010) UKERC Research Atlas Topic: Marine Energy, UK Energy Research Centre, London
- [20] Jacobsson, S. & Bergek, A. (2004) Transforming the energy sector: The evolution of technological systems in renewable energy technology, *Ind. Corp. Chang.* 13 (5), pp815–849
- [21] Augustine, M. et al. (2010) Concept convergence: A framework for improving product concepts, *Computers & Industrial Engineering* 59, pp367–377
- [22] Jeffrey, H. et al. (2013) Accelerating the development of marine energy: Exploring the prospects, benefits and challenges, *Technological Forecasting & Social Change* 80, pp1306–1316
- [23] Teece, D.J. (1986) Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy, *Research Policy* 15 (1986), pp285–305
- [24] Hull, F. & Slowinski, E. (1990) Partnering with technology entrepreneurs, *Research Technology Management* (November-December), pp16–20
- [25] Hamel, G. et al. (1989) Collaborate with your competitors and win, *Harvard Business Review* 133
- [26] Industry Vision Paper (2013) European Ocean Energy Association, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [27] Amanatidou, E. & Guy, K. (2008) Interpreting foresight process impacts: Steps towards the development of a framework conceptualising the dynamics of foresight systems, *Technological Forecasting & Social Change* 75, pp539–557
- [28] Bucher, R. & Couch, S.J. (2013) Adjusting the financial risk of tidal current projects by optimising the “installed capacity / capacity factor”-ratio already during the feasibility stage, *International Journal of Marine Energy* 2, <http://dx.doi.org/10.1016/j.ijome.2013.05.008>
- [29] Bucher, R. (2012) De-risking marine energy investments by extending the regular project implementation by a competitive technology qualification routine, 4th ICOE, Dublin, Ireland
- [30] Sterman, J.D. & Booth Sweeney, L. (2002) Cloudy skies: Assessing public understanding of global warming, *System Dynamics Review* 18(2), pp207–240
- [31] Groesser, S. (2011) Projekte scheitern wegen dynamischer Komplexität: Qualitative Feedbackmodellierung zur Komplexitätsbewältigung, Bern University of Applied Sciences, [www.bfh.ch](http://www.bfh.ch) [10/03/2013]
- [32] Sterman, J.D. (1992) System dynamics modelling for project management, Sloan School of Management, Massachusetts Institute of Technology, Cambridge
- [33] Cooper, K. & Lee, G (2009) Managing dynamics of projects and changes, Proceedings of the International System Dynamics Conference, USA
- [34] Sterman, J.D. (2010) Does formal system dynamics training improve people’s understanding of accumulation?, *System Dynamics Review* 26(4), pp316–334
- [35] Senge, P. (1990) The fifth discipline: The art and practice of the learning organisation, ISBN 978-0553456349, Crown Publishing Group, New York

## **F Publications**

### **F.3 Peer review conference papers**

Bucher, R., Bryden, I.G. (2014b) Overcoming the marine energy pre-profit phase: What classifies the game-changing “array-scale success”?, Proceedings of the 2<sup>nd</sup> Asian Wave and Tidal Energy Conference (AWTEC), Tokyo, Japan



## OVERCOMING THE MARINE ENERGY PRE-PROFIT PHASE: WHAT CLASSIFIES THE GAME-CHANGING “ARRAY-SCALE SUCCESS”?

Ralf Bucher<sup>1</sup> and Ian Bryden<sup>2</sup>

<sup>1</sup>University of Edinburgh, Institute for Energy Systems, Mayfield Road, Edinburgh, EH9 3JL, UK

<sup>2</sup>The University of the Highlands and Islands, Ness Walk, Inverness, IV3 5SQ, UK

Tidal current and wave power have made substantial progress towards commercialization. Based on the successful testing of full-scale prototypes, pioneering tidal arrays are currently implemented by means of direct agreements between developers/investors and device manufacturers. The top-ranked risks for commercial projects (identified as “achieving funding” and “uncertainty in device performance”) are directly intercorrelated as investors’ confidence mainly depends on track records of continuous device operation. Before becoming recognized as a fully mature electricity generation method, marine energy needs to prove a range of referencable project cases. The attainment of this “array-scale success” will represent a major turning point for the marine energy business and is expected to finally trigger large-scale deployment.

**Keywords:** marine energy commercialization, investor confidence, array-scale success, system dynamics modelling

### I INTRODUCTION

Marine renewable energy arises in an era of global interest in carbon-free electricity generation. After significant technological advances in the wave and tidal sectors in the last years, the industry now moves from full-scale prototype testing to the phased implementation of first tidal arrays ranging from 10 to 86 MW [1-3]. These demonstration projects are mainly based on bilateral agreements between developers/investors and leading device manufacturing firms. The global potential of marine energy and the planned investments are substantial. In the UK, The Crown Estate have leased 37 wave and tidal sites with a total capacity of 1,800 MW [4]. The UK Department of Energy and Climate Change informed that up to 300 MW of generation capacity may be deployed by 2020 [5]. For the period up to 2050, installation capacities in the multi-gigawatt range are indicated [6].

Taking into consideration these figures and the projected machinery ratings, the number of devices to be tendered, deployed and operated will be in the range of several thousands. According to RenewableUK, presently 12 full-scale devices with a total output of 9 MW undergo sea trials in UK waters [7].

In the course of this research, the interviewed experts provided estimations for risk levels focusing on the realization of virtual tidal current or wave power reference projects (capacity ~40 MW, implementation ~2025, investment ~120 m€). The top-ranked risks were identified as “achieving funding” and “reliability” (i.e. “uncertainty in device performance”).

### II OBJECTIVE OF THE RESEARCH

Considering a business environment in which other renewables operate price-competitive to conventional sources and the appearance of new forms of hydrocarbon

extraction, the market entry of marine energy is a one-off chance. To enhance the success rate, stakeholder-wide co-ordination and co-operative interaction are required. The top-level driving factors for achieving full-commercial power generation by marine energy were determined by Bucher [8] in the course of a system dynamics-backed analysis of cross-category expert interview data, as: (i) strong and long-term commitment from government; (ii) array-scale success; and (iii) cost reduction.

As singular characteristics of government regulations are outside the range of this research, focus is put on the interim milestone “array-scale success”. The effective preparation and conduction of this game-changing event is seen as the decisive strategic task at the time.

The research is oriented around the hypothesis:

*“Regular commercial marine energy array projects will be realized under institutional financing and according to international procurement principles. To ensure investor confidence, the reliability of the technological concept has to be proven in advance. The application of co-ordinated strategic principles, identified in the course of expert interviews and by system dynamics analyses, facilitates achieving the array-scale success which represents the key interim milestone towards commercialization.”*

To rapidly overcome the present pre-profit phase, the strategic orientation of central stakeholders needs to be regularly evaluated in order to identify joint objectives and to put corresponding measures put into practice. Ideally, the future supplier market will be composed of numerous manufacturing companies offering comparable high-class technology under competitive pricing.

### III RESEARCH PRINCIPLE AND METHODOLOGY

The underlying idea for our research approach is

inspired by a strategic rule known in the theory of games as “look ahead and reason back” [9]. In the present context, this “look ahead” is defined by focusing on the reason of existence of any large-scale power scheme: market competitive electricity generation – and in this case by marine energy. A main principle applied is to holistically integrate the wide spectrum of stakeholder positions in an unbiased and systematic manner. This multi-disciplinary attempt allows an all-encompassing appraisal by avoiding concentrating in a limiting manner on stakeholder-specific views or interests.

For the survey, a four-page questionnaire with a total of 90 questions was elaborated out of which 48 were yes/no questions and 42 of qualitative character referring to stakeholder-related experience. By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was retained for the analysis, corresponding to an effective return rate of 32.4 % which is more than usual for studies of this nature [10]. A total number of 2,129 individual replies had to be grouped to formulate higher-level correlations as basis for the computer-based system dynamics modeling. All semi-structured single person interviews were conducted either face-to-face at the premises of the interviewee or by telephone between June 2012 and April 2013.

Our contribution aims to fulfil the dynamic interplay between trans-organizational knowledge creation, system dynamics-backed information compression and the targeted diffusion of strategic know-how.

#### IV THE GAME-CHANGING “ARRAY-SCALE SUCCESS” AND ITS CONCLUSIVE EFFECTS

##### A) Definition of the term and salient features

Marine energy finds itself in a decisive transition phase with successfully tested full-scale prototypes but an outstanding utility-scale proof of the technological concept. In the course of the expert interviews, the importance to focus on “array-scale activities” and “to get pilot farms built” was repeatedly stressed. Most answers to the question “In which areas is research most required to accelerate the development of marine energy?” referred directly to multi-device arrangements such as “array-scale design”, “hydrodynamic modeling of arrays”, “array-scale maintenance”, “the need for design tools to facilitate cost-effective array-scale development” and “to see first arrays progress through FID<sup>1</sup>”.

As highly sensitive to the success of marine energy, the following aspects were identified: “the lack of investor confidence”, “fragmented initiatives by unexperienced parties”, “demonstrator/technology failures” and “critical events regarding H&S<sup>2</sup> (negative press)”. These factors

underline the importance to “showcase commercial-scale projects/demonstrators” (i.e. to achieve the “array-scale success”) and to improve the credibility of the generation method in order to create a positive investment climate.

The “array-scale success” represents the key interim milestone and has to be seen within the larger picture characteristic for the power industry. For the marine energy technology breakthrough, positive and transparent feedback from a variety of longer term grid-connected and commercially operated multi-megawatt arrays is required. In case first small-scale arrays become operational in 2016/17 as outlined in [7], then the achievement of the “array-scale success” – as per definition – can be expected in the first half of the new decade.

Before becoming recognized as a fully mature and competitive electricity generation method, marine energy needs to prove a range of referencable application cases. The attainment of the confidence-building “array-scale success” will represent a major turning point for the global marine energy business as is expected to finally trigger large-scale deployment. Because of the comprehensive demands on this interim milestone, the hurdle will not be passed by a small number of companies in the course of a singular demonstration project at one specific site.

##### B) Creation of investor confidence

Leete et al. [11] performed a series of interviews with senior finance and industry actors in the marine renewables sector and examined investors’ attitudes towards wave and tidal technologies. They reported that none of four investors previously engaged in venture capital funding of early stage marine energy device development in the UK were likely to do so again. Venture capital investors are discouraged from investing because of high capital requirements and the uncertainty of costs respective future revenues. It is outlined that a track record of continuous device operation of at least 6 months is seen as a pre-requisite for further investments. The authors conclude that at the current stage of development, strategic investment in partnership with industry investors is essential for moving towards commercialization.

Investors profiled by Masini & Menichetti [10] show a clear preference for more mature, proven technologies with only 3 of the 93 investors analyzed having any exposure to wave and tidal energy. Given the small scale of current marine energy developments, investors are able to achieve similar or greater returns on larger developments of more proven energy technologies.

According to Sjöö [12], the following is usually assessed before venture capital investment in renewable energy technologies: regulatory framework, competitive situation, technological risks, market uncertainty and supply chain constraints. Santos et al. [13] emphasize that energy investments have specific characteristics because of (i) their irreversibility; (ii) high levels of uncertainty; and (iii) the flexible timing as the investor might be able to postpone his decision in order to obtain better information. The different funding sources over the technology development and maturation stages are summarized by

<sup>1</sup> Final Investment Decision (see “FID enabling for renewables” by DECC)

<sup>2</sup> Health and Safety



Wüstenhagen [14] as: grants (for R&D), venture capital (for part-scale prototypes), private equity (for full-scale prototypes), debt finance (for first pioneering arrays) and institutional finance (for utility-scale projects).

Aside from the difficulties for venture capitalists to engage, the private company investment in marine energy of over 600 m€ in the last 7 years has built confidence and triggered significant progress [15]. The involvement of major industrials (ABB, Alstom, Andritz, DCNS, Siemens and Voith) as well as the successful testing of full-scale prototypes underlines the commitment in the sector and indicates significant accessible engineering competence.

### C) Project certification to confirm market-readiness

Reliability is an important factor of success for all emerging technologies. In marine energy, the reliability proof remains a major challenge as most devices to date have been in the water only for short periods of less than one year. Reference data is therefore limited. In contrast to offshore wind, tidal current and wave power technology development cannot benefit by the extension of reliable onshore devices. Without any transition period, the maturity of the power machinery equipment and related interfacing systems has to be proven directly under the harsh marine conditions in high energy sites.

Third-party certification is well established in mature industries and means that an independent organization confirms the compliance of a product or service with legal-normative standards, contractual obligations and project-specific technical requirements. The European Marine Energy Centre [16] lists two kinds of certification: type and project certification. Type certification refers to a marine energy converter built in series or to parts of it. It consists of an assessment of the quality management system and the evaluation of the compliance with contractual requirements in the production, manufacturing, deployment and commissioning phases as well as during operation. Within a project certification, it is assessed whether the respective site conditions (e.g. meteorological and oceanographic data, soil properties, environmental aspects and electrical network data) conform to those defined in the contract specification of the converter. According to the authors, the project certificate refers to the design (and changes thereof), manufacturing, installation and commissioning of a marine energy farm including cable lay and grid connection. In the context of proving the “array-scale success”, the integrity assessment of the technological concept – and as such type and project certification – are required. Conformity certificates will be issued for the constituent projects.

In public procurement processes, bidders need to fulfil minimum qualification criteria. In the case of marine energy for device manufacturers the following would serve as evidence of conformity: (i) previously installed converters (type, rating, marine climate, foundation, grid interface, distance to shore); (ii) geophysical and geotechnical conditions; (iii) environmental impact assessment; (iv) operation and maintenance protocols; (v)

H&S log; and (vi) confirmed CapEx<sup>3</sup> and OpEx<sup>4</sup> data.

In the course of the performed expert interviews, a global certification company's representative underlined the importance of certification but also mentioned the need to accelerate the development of robust and reliable marine energy technology and recommended as such to carefully balance progress with a level of risk acceptable to all involved stakeholders.

### D) Developing a market by manufacturer competition

As the long-term perspective of the marine energy industry sector might become principally comparable to the one of wind power, the development of the number of megawatt wind and tidal stream turbine manufacturers – including the respective installed capacities – are depicted together in Fig. 1.

It is encouraging to note that in marine energy the first 1 MW full-scale prototype was deployed in the year 2008 and only 5 years later a minimum of 6 renowned companies count with comparable equipment. In this regard, the momentum for growth in marine energy is significantly higher as it was in wind power where this time span took about 14 years. In the year 1984, in wind power a significant annual capacity increase of a total of 400 MW was realized within a global market environment of only 5 competing MW-turbine manufacturing firms [17].

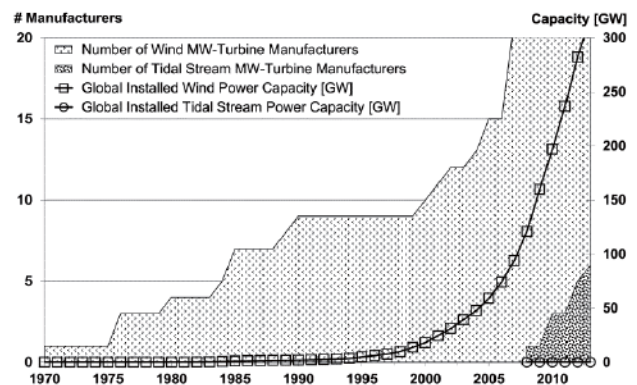


Fig. 1. Comparing the development in wind and tidal stream power: No. of manufacturers & GW<sup>5</sup> installed [18].

Today, full-scale 1 MW+ tidal stream converters are manufactured by major industrials such as for example Alstom (DeepGen), Andritz (HS1000), Atlantis Resources Corporation (AR1000), DCNS (Open-Centre), Siemens (SeaGen) and Voith Hydro (Hy-Tide). Wave energy converters of 500 kW+ rating are produced among others by Aquamarine Power (Oyster1), Pelamis Wave Power (P2), Seatricity (Oceanus) and Wello Oy (Penguin) [7].

Apart from public marine energy support regimes to

<sup>3</sup> Capital Expenditures: pre-development costs, construction costs, electrical systems infrastructure costs

<sup>4</sup> Operational Expenditures: operating and maintenance costs, insurance costs, de-commissioning costs, seabed lease, transmission grid charges

<sup>5</sup> 1 Gigawatt [GW] = 1,000 Megawatt [MW] = 1,000,000 Kilowatt [kW]

help commercialize tidal and wave technologies, strategic partnerships between major utilities and leading device manufacturers are currently in place. By jointly financing and managing projects, the transition from single-device testing towards commercial-scale array deployment is streamlined and the correlated risks are shared.

Actual examples of such partnerships are:

- (i) ScottishPower Renewables has received consent to develop a 10 MW demonstration tidal array on the west coast of Scotland. The "candidate devices" are developed by Andritz Hydro Hammerfest and Alstom. Installation is planned to start in 2016 [19].
- (ii) RWE Innogy develops a 10 MW array off Anglesey, North Wales. The project was granted planning approval in 2013 and will be taken forward by Siemens Marine Current Turbines Ltd. [20].
- (iii) GDF SUEZ plans to install a 3 to 12 MW tidal array pilot plant at Raz-Blanchard in France in 2016. Industrial partnership agreements to deploy Alstom and Voith turbines were signed [21].

It is noteworthy that in the conventional power sector such direct collaborations would be hindering and not in line with current regulations for projects realized under international competitive bidding (ICB<sup>6</sup>). The probability of getting best-available technology at a market-balanced price would be reduced.

#### E) Triggering serial production and cost reduction

After the concept maturity will have been demonstrated by grid-feeding schemes, new potential for cost reduction will be tapped by serial manufacturing processes and due to learning effects forced by the routine implementation of projects under global market competition. Furthermore the identification of yet undiscovered low-cost strategies is expected as a natural element of technology convergence processes.

According to DECC [5], the projected levelised cost of electricity generation (LCOE<sup>7</sup>) will range for UK marine energy in the year 2020 between 20 and 42 c€/kWh. Spain expects LCOE for that period of time of 21 to 33 c€/kWh [22]. Previsic et al. [23] have pointed in similar manner to commercial opening cost of electricity for wave power in the order of 20 to 30 c€/kWh. Until 2020 DECC projects LCOE for onshore wind in the UK of 9 to 15 c€/kWh and for offshore wind of 13 to 22 c€/kWh. RenewableUK [7] believe that the current LCOE for leading tidal stream devices is around 36 c€/kWh compared with 48 c€/kWh for wave power devices.

As onshore wind energy represents the reference for cost-competitive renewable power, it shall be noted that the global average LCOE dropped from 19 c€/kWh in

1992 to 6 c€/kWh in 2014 [24]. Offshore wind farms at very good locations currently achieve LCOE of 11 to 19 c€/kWh [25,26].

Presently the kWh-cost in marine energy are far too high to compete with other renewable or even non-renewable generation options [27]. Taking into consideration the projected LCOE in the UK for 2020, the cost for tidal stream might touch the upper end of the offshore wind range. For the forthcoming years, governmental support programs will be indispensable to further drive research and development [28]. Referring to offshore wind – with a global installed capacity of 5.4 GW [29] – it is expected that still 15 years of further subsidies will be required [30].

Apart from purely assessing c€/kWh generation cost, a unique asset of renewable electricity generation by tidal currents is its predictability due to the known effects of gravitation exerted by the moon and the sun upon the earth. Especially in grids with high portions of volatile renewable generation, grid operators would welcome such long-term and precisely predictable generation capacities. Especially at remote sites with weak grid systems, this might be an economically relevant factor. The overall performance of hybrid systems operating a combination of intermittent solar photovoltaic, wind and reserve-capacity diesel power could be improved.

## V MAIN TECHNOLOGICAL DRIVERS FOR RAPIDLY ACHIEVING THE "ARRAY-SCALE SUCCESS"

### A) Systems engineering approach

When asking for significant potential to decrease the cost for utility-scale project implementations, the CEO of an Irish wave energy converter manufacturer indicated a clear recognition to orientate their development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. The division vice-president of a multi-national engineering conglomerate emphasised the importance to prove that the technology concept works and to focus on end user requirements. Both statements correlate with the central objective in systems engineering as to consider the finally envisaged functionality already in early stages. Apart from applying systems engineering in the primary development of marine energy converters, it is of importance to focus on equipment interplay requirements and to realistically define the system boundaries. As the envisaged large-scale marine energy schemes will be developed in stages and most probably with equipment supplied by different firms, flexible but robust methods must be available to quickly respond to site requirements (e.g. deployment, power evacuation, norms). The functionality checks shall be gradually increase in their complexity.

### B) Multi-applicable technologies and joint concepts

The benefit by working along a robust engineering plan targeting on serial production and large-scale manufacturing was underlined. According to the opinion of a utility's ocean energy project manager, one of the top-priority tasks in the work of academia and research

<sup>6</sup> ICB refers to the selection of the lowest-priced bid under fair and healthy international competition.

<sup>7</sup> LCOE is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.



should be to concentrate on multi-applicable technologies as well as standardizing devices and components (e.g. moving parts, cable connector systems, control interfaces). To finally ensure identical component design and project delivery, effective supply chain management and leveraging logistics are required. Referencing to offshore wind, in [31] it is pointed out that joint installation and maintenance concepts for adjacent wind farm locations significantly decreased offshore installation times and increased the operating efficiency.

### **C) Standardization (look at volume manufacturing)**

The reply of a project developer's head of offshore when asking for the most valuable experience gained by the early movers in the sector was towards the "negative impact by missing standardization". Considering the present grade of standardization, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). A marine renewables engineer employed with a consultancy firm identified the consensus over standardization as a target that appeared more difficult to reach than planned. The overall importance of standardization in marine energy was emphasized by several interviewees when highly appreciating the published results by the standardization group within one of the global top three certification companies. One participant summed up the situation as: "no standards, no results". The level of detail and the date of publishing new industry standards need to be carefully discussed with manufacturing firms. As such counterproductive limitations on confident early-stage R&D initiatives and unnecessary cost impacts can be avoided. A senior contracts expert of an international UK law firm mentioned the need for contract standardization and so-called collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favorable contract terms). Contract splitting (e.g. in turbines, fundament, transformer, inner-park cabling) as applied in offshore wind was recommended.

### **D) Technology convergence**

The emergence of dominant designs in complex technical environments was examined by Murmann & Frenken [32] from a system theory perspective under the aspect of technology standardization. Augustine et al. [33] concentrate in their research on technology convergence and concept evaluation processes in industrial product development. They emphasize that rather than selecting the best among available alternatives, the progression towards better solutions by combining the strengths of all available concepts is a more robust approach for concept improvement. Today, in the marine renewable energy sector there is still high number of technological concepts which is expected to become reduced in the course of competitive project implementations. According to a senior principal surveyor of a global offshore classification society, a top-priority task in their work is towards technology consolidation. A utility's representative underlined the potential to decrease the cost for commercial-scale project implementations by the positive impact of technology convergence. Considering the dynamic development in the wind power sector, it is noteworthy that since the beginning in the 1980s until

today the rotor diameter has increased from 15 to 124 m and the nameplate rating from 50 to 5,000 kW [34]. The next development step in offshore wind is expected to be the introduction of 7 or even 10 MW turbines [35]. In the IEA report "Scenarios & Strategies to 2050" [36] it is outlined that only through technology learning as a result of marketplace deployment the initially higher cost of new technologies can be reduced.

### **E) Knowledge sharing and knowledge transfer**

The limited sharing of knowledge in the industry is uniformly seen by the strategy manager of a public-private partnership and the head of energy of UK's innovation agency as a main reason why the marine energy sector has not developed more rapidly. A senior policy officer of the Scottish government emphasized the need to transfer lessons learnt in the offshore wind industry to marine energy in order to avoid duplication of time and effort. According to the vice-chair of the largest private R&D group in Spain, the transfer of knowledge from other sectors (under consideration of the specific aspects of marine energy) is identified as a top-priority task in the commercialization process. The project manager for the implementation of the world's first commercial breakwater wave power plant outlined that the need to improve the sharing of (bad!) experience and testing data is key. According to his commissioning experience, sometimes unspectacular and cheap items can create unexpected difficulties. To support progress, his position is to openly inform about such complications by explaining why things went wrong and publishing the implemented solution.

### **F) Maximizing collaboration, minimizing competition**

In line with findings on limited sharing of knowledge, a lack of collaboration in the sector was identified. Apart from improving co-operation between the industries, especially a strengthening of the interaction between the device manufacturers and engineering consultancies was called for. With regard to academia, the head of policy of a major UK developer accentuated the need to further intensify international collaboration. A chance to improve the cross-interaction between different renewable energies is seen in identifying prospective synergy effects by inter-coupling the different kinds of carbon-free generation. The artificial competition with on-/offshore wind was criticized by a marine energy development manager as negatively influencing uninterrupted progress. The interviewed head of development of a wave energy device manufacturer – which recently entered into a research and development collaboration with a major offshore wind developer – underlined the attractiveness of exploring prospects by combining wave and wind power. Seeking synergies with other manufacturers considering the use of similar technologies is seen as a natural process. The increasing involvement of major industrials in the marine energy sector is considered as positive and will also support the restructuring of the supply chain.

### **G) Competitive collaboration and inter-firm alliances**

Marine energy needs to assert its position in the competitive (renewable) energy market. Exemplary

strategic alliances on how to develop new products and to penetrate new markets can serve as reference. In a recently published paper from the European Ocean Energy Association [15], clear reference was given towards Airbus which was classified as a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments. Amanatidou & Guy [37] hereto emphasize the increasing importance of knowledge-based industries and focus in the research on aligning existing perceptions by maximizing collaboration and minimizing competition.

#### **H) Contractually optimized risk sharing**

The development manager of an Irish wave energy converter manufacturer explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He stressed the requirement to share risks by collaboration and to fully integrate risk management into project management. A UK law firm contracts expert highlighted that risk sharing shall be contractually optimized to identify the most appropriate risk owners. The experience in negotiating risk sharing is seen as a valuable outcome by the activities of the front-running companies. An owner's representative even recommended that engineering consultancies shall share risk with project developers. Similarly a device manufacturer's executive outlined that engineering consultancies shall share risk with industry. The implementation of appropriate risk sharing between the stakeholders is seen as highly relevant for achieving efficient progress in the sector.

#### **I) Detail complexity and dynamic complexity**

When asking for measures to increase equipment reliability, a renewable energy consultant recommended to "design out complexity and failure points". For managing complexity, the differentiation between detail (or combinatorial) and dynamic complexity as in the complex systems theory [38] is helpful:

- (i) Detail complexity is characterized by many elements and a large number of combinatorial possibilities. Groesser [39] explained that in detail-complex situations methods to reduce complexity might be useful. In the present context, potential to reduce detail complexity is seen in applying systems engineering, standardizing components and using multi-applicable technologies. When taking a look at the wider picture, a reduction of detail complexity can be achieved in the course of commercial project implementations by introducing a "competitive technology qualification routine" (as described further below). The long-term best-performing system would be identified in a transparent and fair process.
- (ii) Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships and the need to integrate hard and soft data [40,41]. Dynamically complex systems usually contain non-linear feedbacks, time delays and accumulations. Cause and effect are subtle and obvious interventions can produce non-obvious consequences. The process

of gradually commercializing marine renewable energy comprises a high level of dynamic complexity because of continuously varying interaction between many heterogeneous stakeholders over a decade's long period of time. Dynamic complexity arises even in simple systems and can usually not be reduced. In order to improve project success rates, Groesser [39] recommends qualitative feedback modeling as a method to analyze and handle dynamic complexity.

Research by Sterman [42] revealed that in conventional project management mainly aspects of detail complexity are considered. Senge [43] underlines that the real leverage in most management situations lies in understanding dynamic complexity. Also according to his research, most established planning tools and analysis methods are designed to handle detail complexity but are not equipped to deal with dynamic complexity.

#### **J) Competitive technology qualification routine**

The interview participants identified reliability concerns as the top-ranked non-commercial risk. On the opposite side poor liability was mentioned as key operational risk. The widespread perception of high cost and unproven reliability was mentioned by the strategy manager of a public-private partnership as negatively influencing the sector. The managing director of a UK financial firm and the vice-president of a Canadian project developer emphasized that concerns for delays and cost-overruns mainly relate to reliability, durability and performance of marine energy converters. A US academic named the need for longer baselines for systems reliability and an R&D vice-chair outlined that reliability is more important than efficiency. According to a Scottish government employee, the failure of devices was the fundamental and greatest single reason for projects being delayed or costs increased. Reasons why the marine energy sector has not developed more rapidly were repeatedly identified in the uncertainty of device performance. The need to demonstrate equipment reliability at utility-scale was formulated by the machinery expert of a global maritime classification society. The section manager of an Irish state agency replied to the question on "Where is research most required to accelerate the development of marine energy?" that reliability and the integrity of devices are essential. When asking for measures by which the cost increase experienced in offshore wind can be avoided in marine energy, a project manager of a large utility recommended to even compromise reliability and cost. As main factors for reaching commercial generation, two senior members of classification societies stressed the prevailing uncertainty about reliability and the need to focus on it. To achieve a satisfactory technology performance record, the experts recommended to put more focus on reliability in system design and to introduce reliability modeling.

In all above interview statements, the key importance of technology reliability was uniformly emphasized. As years will pass until full maturity will be reached, Bucher [44] proposed for early commercial projects a "competitive technology qualification routine" in order to achieve the required safety for investment. The principal idea is to extend the project execution by a qualification procedure



in the course of which different manufacturers' power conversion devices are deployed and operated in real-sea conditions directly in the intended project area for a defined period of time (e.g. 3 months). The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated. The approach represents a transparent and evidence-based selection procedure to reliably identify the most suitable technology for a specific site.

## VI CONCLUSION

The principal objective of this research is to create consolidated strategic know-how to support orientating the marine renewable energy commercialization process. The prevailing top-ranked risks (as "achieving funding" and the "uncertainty in device performance") are directly interdependent as the investors' confidence depends on track records of continuous device operation. In the center of this area of conflict we find the "array-scale success" as passing this key milestone will give confidence in this new industrial sector and de-risk investments in commercial projects. As the efficient preparation and management of the "array-scale success" is of central relevance for the continuous development of the marine energy sector, top-level strategic principles of technical-organizational nature were elaborated and presented.

Based on the referenced hypothesis, the paper makes the following contribution:

*"In case major marine energy industrial competitors accept the high significance of jointly achieving the array-scale success, then the motivation for applying the listed stakeholder-wide co-ordinated strategic principles will be increased. Transparently showcasing the long-term reliability of the technological concept and its improving economic competitiveness will de-risk the sector and create the decisive investor confidence."*

The presented approach of using cross-category expert interview data to create complex system dynamics computer models is seen as a powerful method to keep track of the development and to advance strategy finding.

## VII RECOMMENDATIONS AND FURTHER RESEARCH

Hull & Slowinski [45] demonstrate that co-operative relationships between firms in high technology can bring to market new innovations that neither firm alone could have accomplished. The term "competitive collaboration" was introduced by Hamel et al. [46] for strategic alliances that strengthen companies against outsiders (i.e. other renewables) even as they weaken each partner vis-à-vis the other. The given exemplary strategic alliances on how "to develop new products and to penetrate new markets" can serve as references.

The market entry of the marine renewables and their integration into the existing grid systems represents an ambitious undertaking in a dynamic but long-term oriented business environment. The appraisal of the correlated

grade of complexity is enhanced when splitting it into two: detail and dynamically complex aspects. Nevertheless detail complexity can be reduced by suitable methods to a certain degree, the key for success is seen in handling the involved dynamic complexity. The outlined approach of "expert interviews / system dynamics modelling / application of strategic principles" provides an adequate fundament.

As the introduction of electricity generation by tidal stream and wave energy is an unprecedented initiative with significant investment and risks involved, the flexible adaptation of the commercialization process to prevailing events and dynamic circumstances is essential. In case the maturity of the concept can be shown in the course of the "array-scale success", then there is a prospective future for this new and exciting energy alternative.

## Acknowledgement

The paper is part of a PhD research into "Strategic Risk Management for Tidal Current and Wave Power Projects" at the Institute for Energy Systems, University of Edinburgh, UK. The author is grateful to all participants in the expert interviews and Prof Bryden for his continuous support. Thanks to the anonymous reviewers for providing helpful comments and suggestions.

Table 1. List of participating stakeholders.

<b>Government (associations) &amp; trade organisation:</b> The Scottish Government, Marine Scotland, ETI, Carbon Trust, Department of Energy and Climate Change, The Crown Estate, Scottish Natural Heritage, Centre for Environment, Fisheries & Aquaculture Science, RenewableUK, Technology Strategy Board.
<b>Certifying authorities:</b> DNV, Lloyd's Register.
<b>Investors &amp; lenders:</b> Green Giraffe.
<b>Law firms:</b> Eversheds International.
<b>Academia &amp; research:</b> University of Washington, University of Edinburgh, National Taiwan Ocean University, Irish Marine Institute.
<b>Engineering consultancies:</b> Natural Power, Xodus Group, Tecnalia Research & Innovation, South West Renewable Energy Agency, Royal Haskoning.
<b>Project developers:</b> Emera, EDF, Electricity Supply Board Ireland, Iberdrola.
<b>Owners &amp; operators:</b> ScottishPower Renewables, Ente Vasco de la Energía.
<b>Transmission system operator:</b> Scottish and Southern Energy Renewables.
<b>Device manufacturers:</b> Marine Current Turbines, Pelamis Wave Power, Wavebob, Siemens, Wave Star, Ocean Renewable Power Company.
<b>Offshore contractors:</b> 6 contacted (no feedback).
<b>Test site operators:</b> EMEC, Fundy Ocean Research Centre for Energy, National Renewable Energy Centre, Minas Basin Pulp & Power, France Energies Marines.
<b>NGOs:</b> Greenpeace.
<b>Offshore wind industry:</b> Dong Energy Power.
<b>Oil &amp; gas industry:</b> 4 contacted (no feedback).

## References

- [1] Scottish Government (2013) Major boost for wave & tidal industry, <http://news.scotland.gov.uk> [09/11/2013]
- [2] ScottishPower Renewables (2013) Sound of Islay, [www.scottishpowerrenewables.com](http://www.scottishpowerrenewables.com) [10/05/2013]
- [3] MCT (2013) Skerries Tidal Array secures consent, [www.marineturbines.com](http://www.marineturbines.com) [10/05/2013]
- [4] The Crown Estate (2012) Wave & Tidal Programme: Future Leasing – Industry Engagement Exercise, [www.thecrownestate.co.uk](http://www.thecrownestate.co.uk) [10/05/2013]
- [5] DECC (2011) UK renewable energy roadmap: Department of Energy & Climate Change, London
- [6] The Carbon Trust (2011) Accelerating marine energy: Potential for cost reduction, London
- [7] RenewableUK (2013) Wave and Tidal Energy in the UK, RenewableUK, London
- [8] Bucher, R. (2013) Strategic risk management in ocean energy, 10th EWTEC, Aalborg, Denmark
- [9] Dixit, A.K. & Nalebuff, B.J. (1991) Thinking strategically, ISBN 9780393310351, pp36–37
- [10] Masini, A. & Menichetti, E. (2012) The impact of behavioural factors in the renewable energy investment decision making process: Conceptual framework and empirical findings, *Energy Policy* 40, pp28–38
- [11] Leete, S. et al. (2013) Investment barriers and incentives for marine renewable energy in the UK: An analysis of investor preferences, *Energy Policy* 60, pp866–875
- [12] Sjöö, K. (2008) The influence of uncertainty on venture capital investments in renewable energy technology: An exploratory study, University of Oslo, [www.duo.uio.no/handle/10852/17873](http://www.duo.uio.no/handle/10852/17873) [06/05/2014]
- [13] Santos, L. et al. (2014) Real Options versus Traditional Methods to assess Renewable Energy Projects, *Renewable Energy* 68, pp588–594
- [14] Wüstenhagen, R. & Menichetti, E. (2012) Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research, *Energy Policy* 40, pp1–10
- [15] Industry Vision Paper (2013) European Ocean Energy Association, [www.oceanenergy-europe.eu](http://www.oceanenergy-europe.eu) [20/02/2014]
- [16] EMEC (2009) Guidelines for Marine Energy Converter Certification Schemes, ISBN 978-0580650406
- [17] Moghaddama, N. (2012) Formulating industry strategies, *Renewable Energy* 39, pp299–306
- [18] SI Ocean Project (2013) 1st Technical Report: "Ocean Energy: State of the Art", Compiled by Edinburgh University, Carbon Trust and the Joint Research Council, [http://si-ocean.eu/en/upload/docs/WP3/Technology%20Status%20Report\\_FV.pdf](http://si-ocean.eu/en/upload/docs/WP3/Technology%20Status%20Report_FV.pdf) [30/05/2014]
- [19] BBC News (2013) Alstom devices deal for Sound of Islay tidal array, [www.bbc.com](http://www.bbc.com) [10/06/2014]
- [20] RWE Innogy (2014) Technologies: Marine Energy – Power from the Sea, [www.rwe.com](http://www.rwe.com) [06/05/2014]
- [21] GDF SUEZ (2014) GDF SUEZ signs an industrial partnership agreement, [www.gdfsuez.com](http://www.gdfsuez.com) [06/05/2014]
- [22] IEA-OES (2013) Annual Report, County Report Spain, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2014]
- [23] Previsic, M. et al. (2012) The future potential of wave power in the US, American Geophysical Union, Fall Meeting 2012, abstract #OS53D-08, [www.re-vision.net](http://www.re-vision.net) [06/04/2014]
- [24] Global Wind Report (2013) Annual Market Update, [www.gwec.net](http://www.gwec.net) [06/05/2014]
- [25] Fraunhofer-ISE (2013) Levelized Cost of Electricity, Renewable Energy Technologies, [www.ise.fraunhofer.de](http://www.ise.fraunhofer.de) [06/04/2014]
- [26] International Renewable Energy Agency (2012) Renewable Energy Technologies: Cost Analysis Series, [www.irena.org](http://www.irena.org) [10/04/2014]
- [27] Previsic, M. & Shoele, K. (2013) Cost Reduction Pathways for Wave Energy, 10th European Wave and Tidal Energy Conference, Aalborg, Denmark
- [28] IEA-OES (2014) Ocean Energy Review of Supporting Policies, [www.ocean-energy-systems.org](http://www.ocean-energy-systems.org) [06/04/2013]
- [29] IEA (2013) Technology Roadmap Wind Energy, [www.iea.org/publications](http://www.iea.org/publications) [06/05/2014]
- [30] Karikari-Boateng, K.A. et al. (2013) Reliability of Tidal Turbines using Wind Turbine Experience, 10th EWTEC, Aalborg, Denmark
- [31] Cost Reduction Potentials of Offshore Wind Power in Germany (2013) The German Offshore Wind Energy Foundation, [www.offshore-stiftung.de](http://www.offshore-stiftung.de) [18/02/2014]
- [32] Murmann, J.P. & Frenken, K. (2006) Toward a systematic framework for research on dominant designs, technological innovations and industrial change, *Research Policy* 35, pp925–952
- [33] Augustine, M. et al. (2010) Concept convergence: A framework for improving product concepts, *Computers & Industrial Engineering* 59, pp367–377
- [34] Oceans of Opportunity (2009) Harnessing Europe's largest domestic energy resource, European Wind Energy Association, [www.ewea.org](http://www.ewea.org) [26/07/2010]
- [35] Jensen, D. & Könemann, D. (2010) Alpha Ventus operation offshore, ISBN 978-3870734794
- [36] IEA (2008) Energy technology perspectives, Scenarios & Strategies to 2050, OECD/IEA, Paris
- [37] Amanatidou, E. & Guy, K. (2008) Interpreting foresight process impacts: Steps towards the development of a framework conceptualising the dynamics of foresight systems, *Technological Forecasting & Social Change* 75, pp539–557
- [38] Sterman, J.D. & Booth Sweeney, L. (2002) Cloudy skies: Assessing public understanding of global warming, *System Dynamics Review* 18(2), pp207–240
- [39] Groesser, S. (2011) Projekte scheitern wegen dynamischer Komplexität: Qualitative Feedbackmodellierung zur Komplexitätsbewältigung, *Projektmanagement Aktuell* 22(5), pp18–25
- [40] Sterman, J.D. (1992) System dynamics modelling for project management, Sloan School of Management, Massachusetts Institute of Technology, Cambridge
- [41] Cooper, K. & Lee, G. (2009) Managing the dynamics of projects and changes, Proceedings of the International System Dynamics Conference, Albuquerque
- [42] Sterman, J.D. (2010) Does formal system dynamics training improve people's understanding of accumulation? *System Dynamics Review* 26(4), pp316–334
- [43] Senge, P. (1990) The fifth discipline: The art and practice of the learning organization, ISBN 978-0553456349, Crown Publishing Group, New York
- [44] Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, 4th ICOE, Dublin, Ireland
- [45] Hull, F. & Slowinski, E. (1990) Partnering with technology entrepreneurs, *Research Technology Management* (November-December), pp16–20
- [46] Hamel, G. et al. (1989) Collaborate with your competitors and win, *Harvard Business Review* 133

## **F Publications**

### **F.3 Peer review conference papers**

Bucher, R. (2013) Strategic risk management in ocean energy: A system dynamics approach to the evaluation of 40+ expert interviews, Proceedings of the 10<sup>th</sup> European Wave and Tidal Energy Conference, ISSN 2309-1983, Aalborg, Denmark



# Strategic Risk Management in Ocean Energy: A System Dynamics Approach to the Evaluation of 40+ Expert Interviews

Ralf Bucher

*Institute for Energy Systems, University of Edinburgh  
Kings Buildings, Mayfield Road, Edinburgh EH9 3JL, United Kingdom  
r.bucher@sms.ed.ac.uk*

**Abstract**— The development process of an alternative large-scale electricity generation method from initial academic research until reaching market-competitiveness requires strong political support and long-term stakeholder commitment. With the intention to gain a broad understanding of the characteristics of presently on-going ocean energy activities and the correlated strategic plannings, a comprehensive survey was conducted. In total 44 experts from 13 stakeholder groups provided their knowledge in the form of 2,129 individual replies. To master the amount and complexity of the data, the feedback received was systematically analysed and formed the input for the configuration of detailed cause-effect relationship diagrams. In the paper, the complete process of identifying top-level driving factors from expert interview data by means of computer-assisted system dynamics modelling is explained. The refinement of cross-category expert information represents a reliable basis for knowledge-based decision making with the final objective to accelerate and de-risk the commercialisation of ocean energy.

**Keywords**— Expert interviews, Technology learning, Strategic risk management, System dynamics modelling, Knowledge-based decision making

## I. INTRODUCTION

The identification of a promising way towards commercial power generation by tidal stream and wave power technologies represents a complex task. Independent of public support programmes and governmental regulations, the successful market-entry of ocean energy is confronted by challenges mainly comprising funding and technological barriers.

As for the finally envisaged implementation of 100MW+ ocean energy schemes, the controlled interaction between many stakeholders over a long period of time is required, conventional organisation-internal risk management methods, mainly used in classic power projects, come to their limits.

With the intention to gain a wide-ranging understanding of the characteristics of presently on-going ocean energy activities and the correlated strategic plannings, a total number of 136 representatives from 15 stakeholder groups were contacted. We received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result,

the knowledge of 44 experts from 13 stakeholder groups (government associations & trade organisations, certifying authorities, investors & lenders, insurance companies & law firms, academia & research, engineering consultancies, project developers, owners & operators, transmission system operators, device manufacturers, test site operators, NGOs, offshore wind industry) was ultimately retained for the analysis, corresponding to an effective return rate of 32.4% which is more than usual for studies of this nature [1].

## II. OBJECTIVE OF THE RESEARCH

The academic objective of the present research is on the transparent transformation and refinement of interview-based expert information and holistic knowledge into clear strategic directives. The practice-oriented objective is to understand the characteristics of the main risk complexes in ocean energy and to provide support for optimised decision-making necessary to accelerate the commercialisation of the concept.

The importance of inviting all key stakeholders to actively share information and to commonly contribute to the goal of establishing ocean energy as a mature alternative electricity generation method cannot be underestimated. The research is designed in an open-integrative manner in order to motivate the stakeholders to actively participate and so to facilitate the further technology development and project implementation processes.

## III. DISCUSSION OF RELEVANT LITERATURE

### A. Strategic Risk Management

Conventional risk management procedures are mainly tailored for stakeholder-related duties or project-specific functions. When opening the risk management towards accompanying an “energy system transformation project” as defined by [2] – and for which the development and grid-integration of ocean energy is an example – the considered time frames and the grade of complexity increase. The time horizon must be extended towards a “strategic dimension” which is generally in the order of five to ten years.

Managing the consequential high number of internal and external interfaces, combined with an intensified stakeholder-

intertwining, represents a major challenge for the strategic risk management.

A concept to comprehensively guide the development of a new electricity generation method must be of transparent nature and based on holistic principles. The art is to compress the vast amount of detail information and to handle the dynamic complexity in order to be in the position to identify central parameters, herein called “top-level driving factors”.

As the commercialisation of electricity generation by ocean energy is confronted by significant challenges, a long-term (or strategic) orientation is indispensable. In [3] it is explained that “strategic risk management encompasses the interdisciplinary intersection of strategic planning, risk management and strategy execution”. The authors furthermore conclude that “by reducing uncertainties and seizing opportunities, better performance in achieving an organisation’s objectives is supported”.

To enable effective ocean energy project implementations, reliable and robust risk management routines must be part of the strategic management. Sensitive risk identification, in-depth risk analysis and appropriate risk treatment are indispensable.

### *B. Knowledge Integration and Knowledge-based Decision-making*

Knowledge management within large organisations and the characteristics of cross-functional project implementations are examined in [4]. It is pointed out that it is vital to understand the dynamics of knowledge integration processes and strategic change initiatives, especially when multiple stakeholder groups are involved.

In [5] the characteristics of strategic decision-making are outlined by indicating that “upper level decision makers are routinely required to make sense of a wide variety of unstructured, complex, and often conflicting information in dynamic, uncertain, highly constrained timeframes and real-time environments”. A further reference within a top-management context is given in [6] by explaining that “decisions evolve through a complex, non-linear, and fragment process”. The fact that “strategic decisions usually have no precedent or guide and are often not easily modelled or analysed” is underlined in [7].

Knowledge-based decision-making consists according to [5] of the following phases: after (i) defining the strategic issues and identifying the sources of knowledge either by interviews, brainstorming of document analysis, the (ii) conceptualisation and integration of knowledge is performed. The (iii) formulation of the knowledge model (e.g. by system dynamics techniques) is validated by feedback analysis and for the (iv) final decision-making, the insight gained by operating the simulation tool is used. The authors emphasise that “the linkage between knowledge management initiatives and the achievement of strategic objectives is facilitated through system dynamics”.

The use of system dynamics as a tool for knowledge-based decision-making was proposed by [8] already at the beginning of the sixties.

### *C. Technology Learning derived from Expert Interviews*

Because of the emerging nature of ocean energy, guidance must be taken from neighbouring sectors such as offshore wind, shipbuilding or oil & gas. In contrast to offshore wind, tidal current and wave power technology development does not benefit by extension from reliable onshore devices. As years will pass until full technology maturity is reached, in [9] a project-inherent “competitive technology qualification routine” is proposed in order to achieve the required safety for investment for commercial-scale projects already during the present interim period.

In [10] it is outlined that “a broad participation by stakeholders and an extensive reliance on expert advice are often seen as preconditions for a legitimate and successfully implemented renewable energy policy”. Furthermore it is emphasised that “interview data are considered, apart from policies and committee reports, as adequate”.

The investigation on risks as barriers to investments in renewable energy developments in North Africa, presented in [11], is based on three stages of structured and unstructured expert interviews.

The research described in [12] focuses on technological, economic, social or public barriers and solutions to renewable energy development. The multi-dimensional analyses of the underlying barriers to investment are based on a theoretical framework focussing on stakeholder’s perceptions. After an initial document review, the bulk of data collection is reported to refer to semi-structured interviews with 18 wind energy experts.

### *D. Complex Systems and System Dynamics (SD) Modelling*

A system is defined as “a combination of several elements where each element has an effect on the functioning of the whole and where each element is affected by at least one other element in the system” [13]. Out of many definitions of complex systems, the following provide the best understanding within the context of the present research: (i) a complex system is literally one in which there are multiple interactions between many different components [14], (ii) a complex system is a system in process that constantly evolves and unfolds over time [15], and (iii) a complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large or one in which there are multiple pathways by which the system can evolve [16]. These three definitions certainly fit the situation around the development and maturation of ocean energy on the way towards commercialisation.

As an initial step in approaching the characteristics of complex systems, in the mid-1950s, Forrester [8] developed system dynamics as “a methodology and mathematical modelling technique for framing, understanding, and discussing complex issues and problems”. System dynamics is introduced by [17] as a “manner of systematic thinking that integrates a large number of causal relationships between variables, and simulates real systems through high-speed computer processing power”.

#### IV. RESEARCH APPROACH AND METHODOLOGY

The chosen research perspective allows a broad and all-encompassing view by avoiding concentrating in a limiting manner on stakeholder-specific problems or benefits. The long-term success of the whole concept of power generation by ocean energy is in the focus.

A conclusive risk management strategy intended to support and guide the ocean energy development process must be designed to be capable to integrate the dynamic interplay between the individual interests of numerous stakeholder groups over a decades-long period of time.

As the top-level driving factors identified in the present research represent strategic indicators for the successful commercialisation of ocean energy, it must be ensured that their determination is realised in an impartial and unbiased manner. Consequently, for the underlying information gathering process, a variety of representatives from all key stakeholder groups active in the ocean energy sector were asked to contribute their knowledge and experience. Such an expert interview-based survey ensures to receive front-end insight which is a prerequisite for precise modelling, in-depth simulation and superior-level analysis.

In line with the cross-category approach of the research, the interviewing process was of an open-integrative rather than a detailed-specialist character. The less problem-oriented nature of the interview questions allows the integration of new knowledge and the consideration of interesting personal or stakeholder-specific experiences and recommendations.

In complex systems, the global behaviour emerges out of interactions among constituent components and between components and the environment [18]. The herein applied inductive reasoning (which is behind the so-called bottom-up approach) "works from specific observations to broader generalisations and theories" [19].

The results created by the system dynamics simulations represent superordinate information and correlate with data usually exclusively available to the top management. Based on such information, the "top executives create plans and orders which are eventually passed down the hierarchy" [20].

#### V. EXPERT INTERVIEWS

For the survey, a four-page questionnaire comprising six sections (Calibrating the research study: defining the target project characteristics / Knowledge transfer and learning from neighbouring sectors / Achievements and planning / Cost aspects / Main impact factors on reaching 'full-commercial marine energy' / Risks) with a total of 90 questions was elaborated. The mix of standardised (closed) and non-standardised (open) questions provided the flexibility to adapt to the different backgrounds, perspectives and interests of the participating experts.

The intention behind the first block of questions was to harmonise and to uniformly direct the research. With a focus on Europe, it was investigated when electricity generation by ocean energy will be considered as a common concept and what will be the average megawatt-rating and installation cost of commercial-scale schemes. By this approach it was ensured

to receive replies focussing on a common goal. Without that calibration, one interviewee might have made associations to prototype testing whereas another concentrates on far-future multi-array installations. Utility-scale electricity generation by ocean energy is statistically expected by the interviewees to be mature in the year 2021 for tidal current and in 2024 for wave power. The expected average individual farm ratings were given for tidal current as 36MW and for wave power 38MW at an investment cost of 102m€ respectively 118m€ (which corresponds to 2,900€/kW or 3,100€/kW). All further thoughts and conclusions uniformly refer to 40MW wave and tidal schemes to be implemented between 2020 and 2025 at an estimated cost of 100 m€ respectively 120m€.

In the survey questionnaire 48 out of the 90 questions were of binary character. To the remaining 42 questions, a number of 2,129 individual replies was received which had to be sorted and grouped in order to formulate higher-level correlations as the basis for the subsequent computer-based system dynamics modelling and simulation.

All interviews were conducted and all feedback received between June 2012 and April 2013.

#### VI. MODELLING AND SIMULATION

For the system dynamics model, all positive and negative impact factors on the final objective "full-commercial power generation by ocean energy" were coherently grouped and inter-correlated. The model was built one-on-one to the interview replies so that it directly reflects the experiences and expectations of a wide range of stakeholders.

Out of a total of 234 qualitative replies directly defining the positive and negative impact factors on the final objective, seven positively formulated "representative group terms" were generated and the replies allocated. In a subsequent step, 16 positive (supporting/accelerating/reinforcing) and 22 negative (hindering/delaying/countervailing) "generic terms" were formulated to correlate the individual interview replies in a systematic manner according to their number of occurrence.

In a system dynamics model, the correlations between elements require a precise specification containing the (either reinforcing or countervailing) direction of effect (+ or – algebraic sign) and the impact time behaviour.

Approximate values for the time delays before individual impacts create effect on the final objective (target factor) of "full-commercial power generation by ocean energy" were introduced in the system dynamics model. In the modelling software this is represented in the form of (i) "short term" for before 2015 (symbol ---), (ii) "medium term" for 2015 to 2025 (-|-), and (iii) "long term" after 2025 (-||-).

The system dynamics model in Fig. 1 consists of seven main nodes ("representative group terms") which all feed towards the final objective of "full-commercial power generation by ocean energy" located in the right hand bottom corner.

The qualitative results of the simulation runs are represented in Fig. 2 in the so-called "insight matrix". On the left hand side, the impact factors with negative effect and on the right hand side the factors with positive effect on "full-



commercial power generation by ocean energy” are located. The y-axis represents the increasing level of impact over time. The greater the distance from the axes of coordinates, the more significant the relevance of a factor to the final objective. In the insight matrix, the resulting sum of all split impacts by the “generic term” factors countervailing or reinforcing the achievement of “full-commercial power generation by ocean energy”, are shown. One common insight matrix was created visually displaying the most significant impact factors. The strongest impact factor (#37) serves as reference value to rank all subsequent weaker positive and negative factors.

VII. TOP-LEVEL DRIVING FACTORS AND IMPLICATIONS

Table I displays the ranking of the ten most significant positive and negative impact factors.

The combined ranking of the sixteen highest ranked top-level driving factors from the course-setting system dynamics model “full-commercial power generation by ocean energy” is shown in Table II. The identified “generic term” factors are substantiated by the underlying representative replies received during the expert interviews.

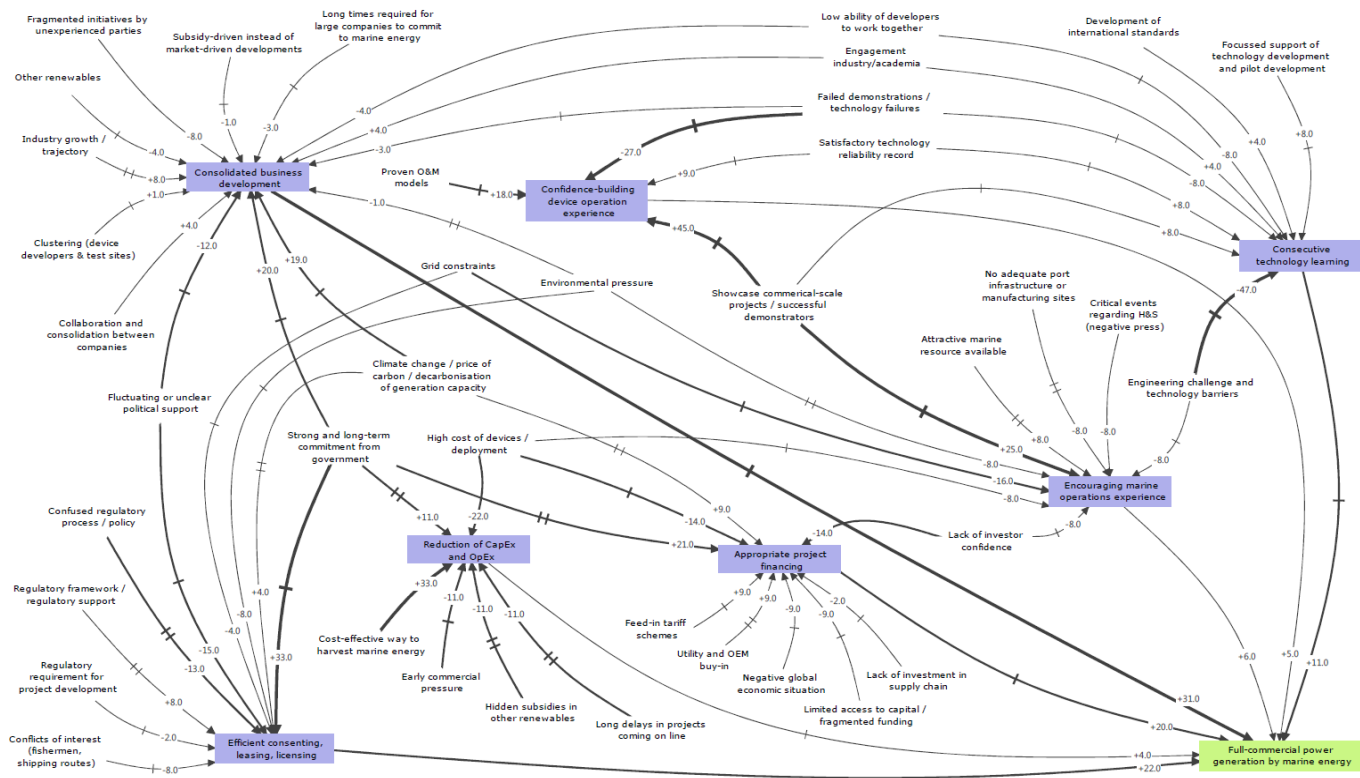


Fig. 1. System dynamics model for “full-commercial power generation by ocean energy”

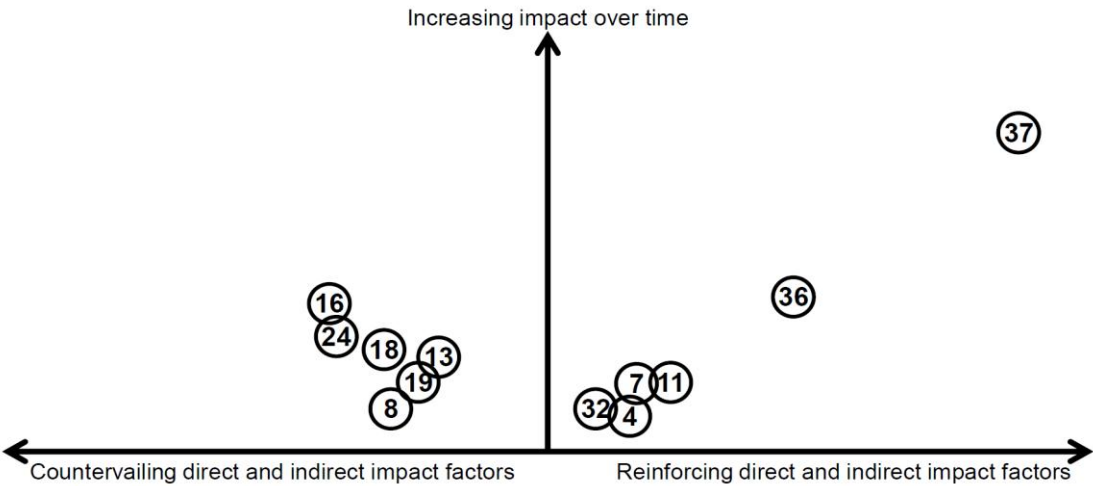


Fig. 2. Insight matrix for “full-commercial power generation by ocean energy”

TABLE I  
SPLIT RANKING OF “TOP-LEVEL DRIVING FACTORS” (POSITIVE AND NEGATIVE IMPACT FACTORS)

Negative (hindering/ delaying/ countervailing)	Ranking	Positive (supporting/ accelerating/ reinforcing)	Ranking
Fluctuating or unclear political support (#16)	47	Strong and long-term commitment from government (#37)	100
Lack of investor confidence (#24)	45	Showcase commercial-scale projects/ (...) demonstrators (#36)	51
Fragmented initiatives by unexperienced parties (#18)	44	Engagement industry/ academia (#11)	22
Critical events regarding H&S (negative press) (#8)	29	Cost-effective way to harvest ocean energy (#7)	18
Grid constraints (#19)	25	Collaboration and consolidation between companies (#4)	15
Environmental pressure (#13)	24	Proven O&M models (#32)	12
The following impact factors of significance are not displayed in the insight matrix:			
Conflicts of interest (fishermen, shipping routes)	23	Climate change/ price of carbon/ decarbonisation	8
High cost of devices/ deployment	20	Satisfactory technology reliability record	7
Failed demonstrations/ technology failures	19	Development of international standards	6
Low ability of developers to work together	17	Regulatory framework/ regulatory support	5

The by far strongest impact factor for achieving the final objective of “full-commercial power generation by ocean energy” is the “strong and long-term commitment from government”. At present the ocean energy sector is characterised by pre-revenue companies and early-stage deployments. The governmental commitment in the form of attractive feed-in tariffs and other support mechanisms is considered as key for the further development of the ocean energy industry and sector. Many interviewees underlined the importance of “strong, consistent and stable political support” with innovation funding mechanisms of a time horizon of 20 years. Apart from funding and fiscal measures, the efficient

management of the consenting process and the ability to secure seabed licenses were emphasised.

The central cluster of impact factors is headed by the need to “showcase commercial-scale projects/ successful demonstrators” which is suitable for a detail examination in a separate system dynamics model. The fundamental importance of achieving confidence in the performance of the core technologies cannot be underestimated and requires soon an array-scale project success. The overall highest ranked negative impact factor is “fluctuating or unclear political support” as the diametrical opposite to the “strong and long-term commitment from government”.

TABLE II  
COMBINED RANKING OF “TOP-LEVEL DRIVING FACTORS” WITH CORRESPONDING REPRESENTATIVE INTERVIEW STATEMENTS

#	Top-level driving factors: Representative interview statements
1	<b>Strong and long-term commitment from government:</b> Funding support; Long-term commitment from government by feed-in tariffs and renewable obligation certificates; Strong, consistent and stable political support is absolute key for the industry; Increased innovation funding mechanisms; Fiscal measures to drive early stage deployments; Government support rules to be in place >20 yrs.; Subsidiary mechanism; Ability to secure seabed; Efficient management of consenting process.
2	<b>Showcase commercial-scale projects/ successful demonstrators:</b> Early project success; Targeted performance; Providing confidence in performance of core technologies; Step-by-step approach (complete one by one); Market maturity.
3	<b>Fluctuating or unclear political support:</b> Suspect/ weakening/ changing political support; Lack of a coherent strategy in the UK; Grey zone (next 5 years are decisive); Start/ stop incentives by the government; Policy decision delays; Lack of consensus from different countries on support mechanisms to use; Missing recognition of renewable energy in public; Moving political positions; Lack of support of administration (legal framework).
4	<b>Lack of investor confidence:</b> Distrust in investment environment; Challenging investment climate.
5	<b>Fragmented initiatives by unexperienced parties:</b> Technology Readiness Levels (TRLs) oversold; Lack of credibility; Reduction of number of technology developers; Too many developers; Competition between the renewable energies.
6	<b>Critical events regarding H&amp;S (negative press):</b> Environmental impact (in case of disastrous event).
7	<b>Grid constraints:</b> Grid access; Uncertainty of getting grid connection in time; Grid updating strategy.
8	<b>Environmental pressure:</b> Environmental impact; Many environmental groups involved; Environmental lobby groups creating increasing number of new restrictions.
9	<b>Conflicts of interest (fishermen, shipping routes):</b> Fishermen (conflict of use); Local fishermen disagreement.
10	<b>Engagement industry/ academia:</b> Critical mass of engaged engineers and scientist; Encouraging research and technology development in coordination with testing facilities.
11	<b>High cost of devices/ deployment:</b> High cost of deployment; Proven O&M costs; Cost we don't know yet; “People want cheap energy”; High cost of wave and tidal.
12	<b>Failed demonstrations/ technology failures:</b> Test failures; Uncertainty about technologies (very experimental, fragile); Technology performance; Lack of industry success stories.
13	<b>Cost-effective way to harvest ocean energy:</b> Cost improvement (realistic); Cost-effective way to harvest ocean energy (techno-economic optimum); Minimising levelised cost of electricity; Ability to bring cost of power generation down.
14	<b>Low ability of developers to work together:</b> More collaboration (too many people doing the same things); Lack of sharing (bad experiences (explaining why things went wrong); Limited knowledge sharing in industry.
15	<b>Collaboration and consolidation between companies:</b> Market certainty; Knowledge transfer from relevant industries (oil&gas).
16	<b>Proven O&amp;M models:</b> O&M involvement; O&M methodologies; Validated O&M models; O&M cost reduction.

Highly sensitive to the success of ocean energy are critical “start/ stop incentives from government” especially when considering the representative interview statement that “the next five years are decisive”.

The “lack of investor confidence”, “fragmented initiatives by unexperienced parties”, “critical events regarding H&S (negative press)” and “failed demonstrations/ technology failures” were identified as significantly hindering and countervailing for the development of the ocean energy sector. Those four factors underline the need to timely “showcase commercial-scale projects/ demonstrators” as technology failures and negative press will trigger a lack of credibility and negatively influence the investment climate. In the course of the ongoing technology convergence process, the number of technological concepts will decline and the technology readiness level increase. Furthermore identified impact factors such as “grid constraints”, “environmental pressure” and potential “conflicts of interest (fishermen, shipping routes)” underline the wide-ranging spectrum of tasks to adequately deal with.

The need for an in-depth “engagement industry/ academia”, the identified “low ability of developers to work together” and the need for an improved “collaboration and consolidation between companies” emphasise a key problem of the sector: the “limited knowledge sharing in industry” and the widely excluded “sharing of (bad) experiences”. A modern positive organisational error management culture as described in [21] would help to reduce the promotion of error consequences and minimise the reported situation that “too many people are doing the same things”. Similarly in ranking, the negatively impacting “high cost of devices/ deployment” underlines the importance of finding a “cost-effective way to harvest ocean energy” and the need for “proven O&M models”.

A third group of impacts is headed by global aspects such as “climate change/ price of carbon/ decarbonisation of generation capacity”. The aim to achieve “satisfactory technology reliability record” requires the continuous “development of international standards” within a motivating “regulatory framework” and by “regulatory support”.

TABLE III  
RANKING OF “GROUPED TOP-LEVEL DRIVING FACTORS” WITH MILESTONES

<ul style="list-style-type: none"> <li>+Strong and long-term commitment from government</li> <li>–Fluctuating or unclear political support</li> <li>–Grid constraints</li> <li>–Environmental pressure</li> <li>–Conflicts of interest (fishermen, shipping routes)</li> <li>+Engagement industry/ academia</li> </ul>	<b>1. Government support</b> (impact: 241)
<ul style="list-style-type: none"> <li>+Showcase commercial-scale projects/ demonstrators</li> <li>–Fragmented initiatives by unexperienced parties</li> <li>–Critical events regarding H&amp;S (negative press)</li> <li>–Failed demonstrations/ technology failures</li> <li>–Low ability of developers to work together</li> <li>+Collaboration and consolidation between companies</li> </ul>	<b>2. Array-scale success</b> (impact: 175)
<ul style="list-style-type: none"> <li>–Lack of investor confidence</li> <li>–High cost of devices/ deployment</li> <li>+Cost-effective way to harvest ocean energy</li> <li>+Proven O&amp;M models</li> </ul>	<b>3. Cost reduction</b> (impact: 95)

In Table III the ranking of the “grouped top-level driving factors” and consequentially defined milestones are shown.

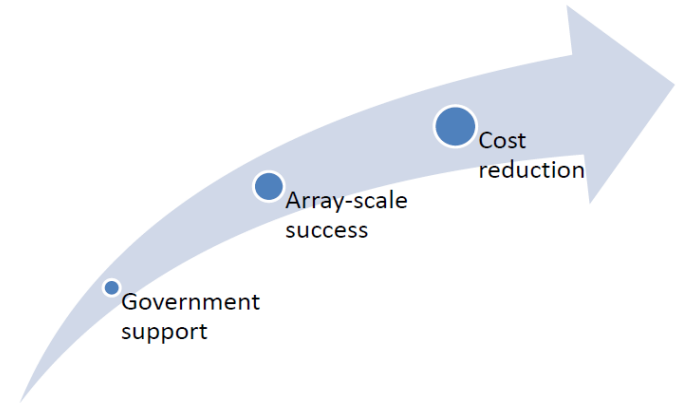


Fig. 3. Milestones in consecutive order according to impact level ranking

In Fig. 3 the milestones derived from the system dynamics simulation on the final objective of “full-commercial power generation by ocean energy” are shown in their consecutive order according to their grouped impact level ranking.

## VIII. CONCLUSIONS AND FURTHER RESEARCH

Based on an extensive empirical database gained during 44 expert interviews and by the use of system dynamics simulation software, the top-level driving factors essential for the consecutive progress in the ocean energy sector were identified and concentrated into three milestone terms:

1) *Government support*: The “strong and long-term commitment from government” represents the fundament for the further progress of the presently still – compared to other power generation methods – embryonic sector. Early stage developments mainly depend on coordinated funding mechanisms and fiscal measures as well as the efficient management of the consenting process.

2) *Array-scale success*: The 2<sup>nd</sup> strongest top-level driving factor to “showcase commercial-scale projects/ successful demonstrators” forms the essential element of this interim milestone which will trigger the further development. In order to examine the reinforcing and countervailing impacts on “full-commercial power generation by ocean energy”, two more in-depth system dynamics models need to be developed.

3) *Cost reduction*: After having demonstrated a successful array-scale scheme, the levelised cost of energy will decline by serial manufacturing effects and technology convergence.

The presented system dynamics analysis was designed with the intention to streamline and de-risk the development of ocean energy as well as to accelerate project developments promoting this new and clean electricity generation method.

The paper shall conclude with a convincing statement given by one interviewee:

*“Generally, if device developers can successfully operate their demonstration devices at a high level of availability for an extended period of time (at least 3 years) then most of the other desirable outcomes, such as investment, takeovers by large companies, grid upgrades and so on, would follow automatically.”*

## ACKNOWLEDGEMENTS

The paper is part of a PhD research into 'Strategic Risk Management for Tidal Current and Wave Power Projects' at the Institute for Energy Systems, University of Edinburgh, UK. The author is grateful to all participants in the expert interviews and Prof Ian Bryden for his continuous support and the inspiring discussions. Thanks to the anonymous reviewers for providing helpful comments and suggestions.

## REFERENCES

- [1] Masini, A. & Menichetti, E. (2012) The impact of behavioural factors in the renewable energy investment decision making process: Conceptual framework and empirical findings, *Energy Policy* 40, pp28–38
- [2] Söderlund, J. (2010) Knowledge entrainment and project management: The case of large-scale transformation projects, *International Journal of Project Management* 28, pp130–141
- [3] Frigo, M. L. & Anderson, R. J. (2009) Strategic risk assessment: A first step for improving risk management and governance, *Strategic Finance*, pp25–33
- [4] Huang, J. C. & Newell, S. (2003) Knowledge integration processes and dynamics within the context of cross-functional projects, *International Journal of Project Management* 21, pp167–176
- [5] Yim, N.-H., Kim, S.-H., Kim, H.-W. & Kwahk, K.-Y. (2004) Knowledge-based decision-making on higher level strategic concerns: System dynamics approach, *Expert Systems with Applications* 27, pp143–158
- [6] Bennett, R. H. (1998) The important of tacit knowledge in strategic deliberations and decisions, *Management Decision*, Vol. 36, No. 9, pp589–597
- [7] Dean, J. W. & Sharfman, M. P. (1993) Procedural rationality in strategic decision-making, *Journal of Management Studies*, Vol. 30, pp587–610
- [8] Forrester, J. W. (1971) Counterintuitive behaviour of social systems, *Technology Review*, Vol. 73, No. 3, pp52–68
- [9] Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, Conference Proceedings of the 4th International Conference on Ocean Energy, Dublin
- [10] Uba, K. (2010) Who formulates renewable-energy policy? A Swedish example, *Energy Policy* 38, pp6674–6683
- [11] Komendantova, N., Patt, A., Barras, L. & Battaglini, A. (2009) Perception of risks in renewable energy projects: The case of concentrated solar power in Africa, *Energy Policy* 40, pp103–109
- [12] Richards, G., Noble, B. & Belcher, K. (2012) Barriers to renewable energy development: A case study of large-scale wind energy in Saskatchewan, Canada, *Energy Policy* 42, pp691–698
- [13] Rapoport, A. (1986) General system theory: Essential concepts & applications, *Cybernetics and systems series*, Abacus Press, Kent
- [14] Rind, D. (1999), Complexity and climate, *Science* 284, 105, pp105–107
- [15] Arthur, W. B. (1999) Complexity and the economy, *Science* 284, 5411, pp107–109
- [16] Whitesides, G. M. & Ismagilov, R. F. (1999) Complexity in chemistry, *Science* 284, 105, pp89–92
- [17] Wu, J.-H., Huang, Y.-L. & Liu, C.-C. (2011) Effect of floating pricing policy: An application of system dynamics on oil market after liberalisation, *Energy Policy* 39, pp4235–4252
- [18] Crespi, V., Galstyan, A. & Lerman, K. (2008) Top-down versus bottom-up methodologies in multi-agent system design, *Autonomous Robots*, Vol. 24, No. 3, pp303–313
- [19] Burney, S. M. (2008) Inductive & deductive research approach, Department of Computer Science, University of Karachi, available from: [www.drburney.net](http://www.drburney.net) [accessed 13/02/2013]
- [20] Nonaka, I. & Takeuchi, H. (1995) The knowledge creating company: How Japanese companies create the dynamics of innovation, Oxford University Press, pp125–127
- [21] Van Dyck, C., Frese, M., Baer, M. & Sonnentag, S. (2005) Organisational error management culture and its impact on performance, *Journal of Applied Psychology*, Vol. 90, No. 6, pp1228–1240

## **F Publications**

### **F.3 Peer review conference papers**

Bucher, R. (2012) De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine, Proceedings of the 4<sup>th</sup> International Conference on Ocean Energy, Dublin, Ireland

# De-risking utility-scale marine energy investments by extending the regular project implementation by a competitive technology qualification routine

Ralf Bucher

Institute for Energy Systems, University of Edinburgh  
Kings Buildings, Mayfield Road, Edinburgh EH9 3JL, United Kingdom  
E-mail: r.bucher@sms.ed.ac.uk

## Abstract

Today's conventional power projects are realised within an established framework of proven project implementation concepts and mature technology. The equipment procurement is typically realised by international competitive bidding within a balanced system of international standards and guidelines.

Marine energy in contrast finds itself in a transition phase from implementing first arrays with full-scale devices – enabled by direct agreements between utilities and manufacturers – towards becoming an accepted alternative electricity generation method. To successfully handle the challenges on the way to full commercialisation, appropriate risk reduction and implementation concepts are required.

The principal idea outlined in this paper is to extend the execution of utility-scale marine energy projects by a competitive technology qualification routine during which different manufacturers' power conversion devices are installed and operated in real-sea conditions in the project area for a defined period of time. The individual device performance is assessed and the manufacturer of the best-ranked system is awarded the principal contract. Non-successful competitors are partly compensated.

The presented approach represents a transparent evidence-based selection procedure to reliably identify the most suitable technology for a specific site and will increase the predictability of the economic performance of large-scale projects.

**Keywords:** Project risk reduction, evidence-based selection procedure, competitive technology qualification routine, optimised project phasing.

## 1. Focus of the research

In contrast to offshore wind, tidal current and wave power technology development does not benefit by

extension from reliable onshore devices. As the reliability proof of marine energy equipment has to be provided under harsh marine conditions, fundamentally different technology qualification routines and deployment strategies compared to classic power projects are required.

The following aspects represent the decisive success factors for investors in the course of the planning and implementation of long-term reliable, cost-effective and environmentally sound marine energy farms:

- a. How can the safe identification of the best-suitable tidal energy converters (TECs) or wave energy converters (WECs) be ensured for a specific site?
- b. Which measures simplify the integration and operation of multi-megawatt intermittent generation in an existing high-voltage transmission system?

The presented competition-based concept to de-risk commercial-scale marine energy projects is inspired by experience in the offshore wind and hydropower sector, the space craft industry and robot vehicle development. In the mentioned sectors quick and clear results were achieved within complex project environments by transparently identifying best-suitable technologies.

## 2. Accelerating the commercialisation of marine energy

### 2.1 Streamlined technology learning

In the IEA report 'Scenarios & Strategies to 2050' it is outlined that most new technologies have higher costs than the incumbents. It is only through technology learning as a result of marketplace deployment that these costs are reduced and the product adapted to the market. Furthermore the report identifies for the marine energy sector the need for 'deployment and technology learning' and emphasises the presently required governmental support to enhance deployment programmes [1].

By integrating device manufacturing companies into the early stages of commercial projects, project-specific



industrial research becomes highly focussed and the identification with the project is intensified. By creating an appropriate framework with market-driven mechanisms, the naturally slow technology evolution process can be accelerated.

In [2] the emergence of dominant designs in complex technical environments is examined under the aspect of standardisation of technologies. In wind power, for example, 3-blade rotors today represent the dominant design, whereby in marine power technology such identification processes are still outstanding.

## 2.2 Signs of a transition phase: direct partnerships between utilities and manufacturers

Apart from various public marine energy support regimes to help develop and commercialise wave and tidal technology, strategic partnerships between major power utilities and leading device manufacturers are presently in place. By jointly financing and developing projects, the transition from installing single device prototypes or arrays of full-scale devices in real-sea conditions towards full commercialisation can be streamlined and the correlated risks shared/reduced.

Actual examples of such partnerships are:

- i. ScottishPower Renewables and Andritz Hydro Hammerfest are testing the HS1000 tidal energy generation device at EMEC and are proposing to develop a 10 MW demonstration tidal array [3].
- ii. E.ON and Pelamis have a working agreement to maximise the learning from operating and maintaining the P2 wave energy converter. The experience gained will be used by E.ON in the development of a 50 MW wave farm [4].
- iii. RWE Innogy and Voith Hydro announced the installation of a 1 MW marine tidal current turbine at EMEC for a 2-year trial operation [5].
- iv. Vattenfall and Wavebob/Pelamis operate a 3-year programme to test machines at EMEC [6].
- v. EDF and OpenHydro develop a pilot farm of 4 tidal turbines off the coast of Paimpol-Bréhat [7].
- vi. Victorian Wave Partners and Ocean Power Technologies/Lockheed Martin have entered into an agreement to develop a 19 MW wave-energy project [8].

It is noteworthy that in the conventional power sector such direct collaboration would be hindering and not in line with international competitive bidding (ICB) procedures. The probability of getting best-available technology at a competitive price would be reduced.

## 2.3 Interview-based risk complex identification

The simplified term 'offshore is not offshore' as one of the summary points in [9] emphasises that each offshore (wind) site has its own specifications and requirements. Because of the proposition to install marine energy devices specifically in areas with high tidal current or wave energy densities, this perception becomes even more relevant.

In the course of a recent interview series on 'strategic risk management for tidal current and wave power projects' with key stakeholders conducted by the author, the following aspects (focussing on technology and implementation) were identified as major requisites for a project's success:

- marine operations experience;
- reliability records based on marine testing;
- a system engineering approach; and
- proven O&M costs.

The above list reflects that the lack of long-term experience with devices operating in the sea represents one of the challenges in the commercialisation of marine energy. In order to reach full maturity, adapted project implementation concepts are required.

## 2.4 An outlook on future marine energy projects

According to [10] the commercial deployment of wave and tidal current could amount to 300 MW (approximately 0.9 TWh) in the UK by 2020. Much larger scale deployment is anticipated in the period beyond 2020. At that time a range of mature WECs and TECs for different tidal regimes or wave climates are expected to be on the market.

By means of ICB the full market spectrum will then become accessible to project developers without excluding any device manufacturer by any form of bilateral agreements. Apart from cutting-edge projects at extreme sites, direct affiliations by utilities and device manufacturer will become obsolete.

# 3. De-risking marine energy investments

## 3.1 Competitive technology qualification routine

The principal idea is to extend the execution of utility-scale marine energy projects by a competitive technology qualification routine during which different manufacturers' power conversion devices are installed and operated in real-sea conditions for a defined period of time. The individual device performance is continuously assessed and the best-ranked system is selected for the final full-scale park implementation.

Non-successful competitors are compensated to partly cover their design, manufacture, installation, O&M and de-commissioning costs based on previously fixed rates. Their devices would have to be removed.

The key incentive for a device manufacturer to participate in the competitive technology qualification routine will be to achieve market acceptance and the perspective to win the principal contract for the full-scale park implementation.

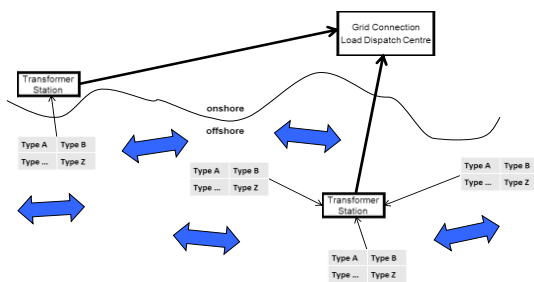
The open competition with subsequent performance assessment represents a transparent decision-making process encouraging the implementation of commercial projects with improved investment security. The total market spectrum is addressed and the best-performing converters are identified under competitive conditions and a long-term basis.

Whereas in order to guarantee an effective multi-manufacturer technology qualification routine for TECs/WECs, it must be ensured that the basic technological array infrastructure (i.e. common systems such as inner-park cabling, transformer stations, array control centre, grid connection, interface to load dispatch centre) is operational in advance providing of manufacturer-independent interfaces.

Apart from legal and commercial requirements, in the tender documents for the technology qualification routine the following has to be precisely specified:

- marine characteristics (tidal regime, wave climate, seabed composition and bathymetry);
- near-by infrastructure (ports, vessels, etc.);
- interface data (connection voltage, control and protection system characteristics); and
- health and safety requirements.

During the performance contest the long-term reliability of each power generation concept will be tested. To identify the suitability of the participating TECs/WECs at different sites within the project area, Fig. 1 indicates that one TEC/WEC will be deployed in each representative sector by each manufacturer A to Z. By this approach the complete range of marine conditions existing in the project area are covered.



**Figure 1:** Exemplary arrangement of TECs/WECs participating in competitive technology qualification routine

By this modular concept, equipment manufacturers can maintain their company-specific component design and have only to adapt to the specified common systems and logic interfaces. A high level of standardisation simplifies the installation and replacement of devices and prepares for an efficient operation and maintenance of the marine energy park.

### 3.2 Experience in other sectors and industries

Competitive technology qualification and concept selection processes have been used at:

- a. the Alpha Ventus Wind Farm: Twelve 5 MW turbines were implemented 45 km off the shore in waters 30 m deep using an innovative approach: two types of turbines were built on two different types of foundations (tripods or jackets) using various construction methods. The experience gained by different designs and the combination of concepts provided valuable information regarding efficiency and reliability, which are crucial for future offshore project realisations [11].

- b. a 70 MW pumped storage hydro-electric scheme in Germany: During the planning phase a small number of construction/engineering consortia were invited to elaborate plant concepts comprising all civil and electro-mechanical works and to submit binding offers. The most advantageous design and construction concept was awarded for implementation and the other participants were compensated for their engineering effort according to the cost items listed in their original bid. By this approach, various state-of-the-art fixed-price plant concepts were made accessible at moderate cost which considerably reduced the total project risk at an early stage [12].
- c. the Ansari X Prize: A US\$ 10,000,000 prize was offered for the first non-government organisation to launch a reusable manned spacecraft into space twice within two weeks aiming to spur the development of low-cost spaceflight. The goal was selected to help encourage the space industry in the private sector and required a private vehicle capable of flying a pilot to 100 km altitude. 26 teams from around the world participated, ranging from volunteer hobbyists to large corporate-backed operations. After two successful competitive flights the price was awarded in 2004 for 'SpaceShipOne' which produced the prototype of the spacecraft that will be used by Virgin Galactic for commercial sub-orbital spaceflights [13].
- d. the DARPA Urban Challenge: From originally 89 teams applying, 39 were invited to a rigorous eight-day vehicle testing period at which autonomous vehicles had to prove their capability of driving in traffic, performing complex manoeuvres such as merging, passing, parking and negotiating intersections. 11 teams were selected for participation in the final event in which the robots had to navigate in city streets together with manned and unmanned vehicles. After a run-time of over 4 hours the first robot crossed the finish line. The winning team was awarded US\$ 2,000,000 [14].

As different as above examples are with regard to technological aspects, their daily relevance and the correlated amount of investment, they have one aspect in common: in all cases a widespread research and market spectrum became accessible leading to the automatic identification of best-suitable concepts that can provide a solid basis for further development phases or even direct project implementations.

### 3.3 Systematic performance assessment

The tasks of concept selection represents a multi-criteria decision making process for which the accurate definition of the weighting factors and scoring criteria is essential.

As the decision for an energy converter system in a competitive technology qualification routine for a marine energy park will be based on the experience made from the time of tendering until the end of the



test operation period, the evaluation criteria have to cover a widespread contractual and technical spectrum. For tidal current and wave power projects the pre-defined evaluation criteria applicable might be:

- grade of delivering project on time, budget, quality;
- achieved energy yield, capacity factor, efficiency, number of grid-connected operation hours;
- amount of maintenance and cost of spare parts used;
- equipment condition at the end of trial operation;
- extraordinary events, unplanned shutdowns; and
- 'soft factors' such as quality of cooperation, sharing of knowledge, troubleshooting capability, etc.

A comprehensive picture of the performance of each participating manufacturer and his device/technology can be gained by analysing the progress from the award of the partial contract up to the experience during grid-connected operation. According to the pre-defined criteria, the performance and quality of all deployed TECs/WECs are uniformly analysed in a transparent and fair manner. The best-rated competitor(s) is/are either directly awarded for the principal contract or is/are exclusively invited to submit proposals for this subsequent project phase.

## 4. Advance high-risk phases to early stage

### 4.1 Conventional power project phasing

The project phasing applied in conventional power projects according to the 'Definition of Services Guidelines by FIDIC' [15] is shown in the following:

- phase I pre-design
- phase II concept design
- phase III schematic design
- phase IV detailed design
- phase V building permission application
- phase VI procurement / award of contract
- phase VII construction & installation
- phase VIII post-construction

In Fig. 2 a standard project phasing according to FIDIC is shown:

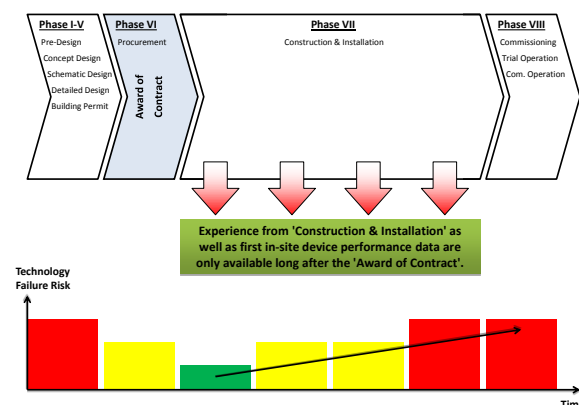


Figure 2: Conventional power project phasing

The correlated expectable technology failure risk levels are displayed qualitatively in 3 categories: low risk (green), medium risk (yellow) and high risk (red).

It can be found that high risk areas are located towards the end of the project implementation, which is unfavourable. Valuable feedback is not available in time to effectively reduce the correlated technical and organisational risks.

### 4.2 Optimised marine power project phasing with a competitive technology qualification routine

In utility-scale projects usually proven technology with extensive reliability records is used. As several years will pass until full technology maturity is reached in marine energy, for an interim period the required safety for investment can be ensured by a project-inherent competitive technology qualification routine.

A marine energy farm will be partly composed by proven elements successfully used in the offshore wind sector (power take-off and grid connection) being tendered and installed by known procedures and on the other hand by innovative tidal current or wave power technology. Consequently special concentration must be given to the sensitive elements being principally addressed in project phases VI and VII.

Contrary to conventional power projects and in line with the requirements of the competitive technology qualification routine, the decisive project phases are further divided as follows:

- phase VI procurement / award of **partial** contract
- phase VII-A construction & installation (stage I)
- phase VII-B competitive technology qualification
- phase VII-C award of **principal** contract
- phase VII-D construction & installation (stage II)

Fig. 3 shows an optimised project phasing including a competitive technology qualification routine.

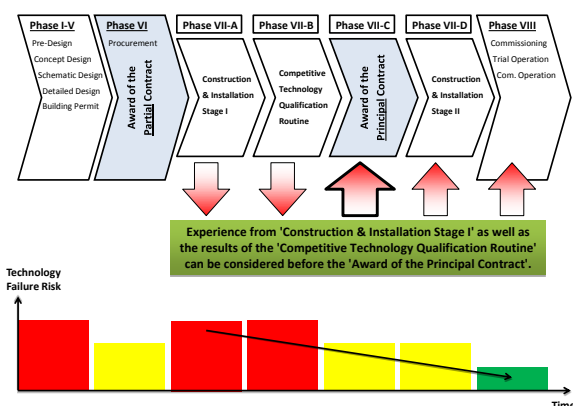


Figure 3: Optimised project phasing for pioneering utility-scale marine energy projects

By this project phasing stage I construction and installation experience as well as operational results gained during the technology qualification routine can be considered before awarding the principal contract.

Apart from the partial contract, which exclusively covers the TECs/WECs competing in the qualification, the common systems have to be tendered at time.

Contrary to the arrangement in Fig. 2 the risk levels decline towards the end of the project implementation.

## 5. Conclusions

The approach presented represents a transparent and evidence-based decision-making process in order to reliably identify the most suitable machinery equipment for a specific marine site. The general intention is to increase the predictability of the economic performance of the underlying commercial project and to further encourage the implementation of utility-scale projects. By the presented concept the full market spectrum becomes accessible and the best-performing devices are identified under real marine conditions and with a long-term perspective.

Referencing to the two introductory questions and the presented ideas, it can be concluded that:

- the safe identification of the best-suitable energy converters for a specific site is substantially supported by a competitive technology qualification routine; and
- the integration and operation of multi-megawatt intermittent generation in an existing high-voltage transmission system is simplified by the initial commissioning of a temporary array with a limited number of TECs/WECs in the course of the competitive technology qualification routine.

Combining the operational experience gained by different make and type TECs/WECs during the competitive technology qualification routine will trigger an improvement of the project performance and prepare for a reliable full-scale park. In [16] it is emphasised that rather than only selecting the best among alternatives, the progression towards better solutions can be found in combining the strengths of all available solutions within given constraints which will finally represent a more robust approach for the concept improvement. New ideas might be triggered.

The presented competitive technology qualification routine transports project-specific industrial research objectives into a straight-forward project environment. The trade-off between the time required for utility-scale project implementation and the finalisation of the maturation process can be optimised if the relevant processes are combined in a systematic manner and guided by transparent rules.

## 6. Recommendations

As each marine project is characterised by individual requirements and constraints, with a guided technology qualification process within a competitive project environment, the best suitable concepts can be identified.

Effective mechanisms to accelerate utility-scale tidal current and wave power project implementations require the close coordination of the interests of the project developer and the equipment manufacturer.

Different to classic power projects, in marine energy at the present stage the hand-in-hand completion of the

technology maturation process and the efficient set-up of projects is necessary. Quick progress rates can be achieved when the project configuration supports both objectives by a joint and iterative process. Considering the complex marine environment and the highly innovative technology used, appropriate contracting methods are necessary for the different project stages.

By inviting the industry to perform within utility-scale projects, the confidence in the sector is improved and the maturation process accelerated.

## Acknowledgements

The author is grateful to all participants in the expert interviews on 'strategic risk management for tidal current and wave power projects' conducted in June 2012 and Prof Bryden at the IES for his continuous support and inspiring discussions.

## References

- [1] International Energy Agency (IEA), Energy technology perspectives, Scenarios & Strategies to 2050, OECD/IEA Paris, France, 2008
- [2] Murmann, J.P., Frenken K.: Toward a systematic framework for research on dominant designs, technological innovations, and industrial change, Research Policy 35 (2006) 925–952
- [3] [www.scottishpowerrenewables.com](http://www.scottishpowerrenewables.com), 17.07.2012
- [4] [www.pelamiswave.com](http://www.pelamiswave.com), 17.07.2012
- [5] Voith Hydro and RWE Innogy install marine tidal current turbine off the Scottish coast, RWE and Voith press releases, [www.rwe.com](http://www.rwe.com) and [www.voith.com](http://www.voith.com), accessed on 19.11.2010
- [6] [www.vattenfall.com](http://www.vattenfall.com), 17.07.2012
- [7] [www.openhydro.com](http://www.openhydro.com), 17.07.2012
- [8] [www.oceanpowertechnologies.com](http://www.oceanpowertechnologies.com), 17.07.2012
- [9] E.ON Climate and Renewables – Offshore Wind Energy Factbook, 04/2010, [www.eon.com](http://www.eon.com), 02.10.2010
- [10] UK Renewable Energy Roadmap, Department of Energy & Climate Change, 3 Whitehall Place, London SW1A 2AW, URN 11D/698, July 2011
- [11] Alpha Ventus – A pioneering project, International Sustainable Energy Review, Issue 2, 2010
- [12] Tenders Worldwide, [www.market.gov.rw](http://www.market.gov.rw), 26.10.2010
- [13] Composite spacecraft wins X-prize, Reinforced Plastics, Vol. 48, Issue 10, November 2004, Page 5
- [14] Defense Advanced Research Projects Agency (DARPA) Urban Challenge 2007, [www.darpa.mil/grandchallenge](http://www.darpa.mil/grandchallenge), 26.10.2010
- [15] FIDIC Estonia Seminar, Policy and Contract Trends, Peter Boswell, General Manager, FIDIC (Fédération Internationale des Ingénieurs-Conseils), 10/2010
- [16] Augustine, M. et al.: Concept convergence process: A framework for improving product concepts, Computers & Industrial Engineering 59 (2010) 367–377